

Sea Level Rise and Storm Surge

Incorporating Uncertainty and Equity into Transportation
Planning for the San Juan Metropolitan Area, Puerto Rico

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Abstract:

Hurricane Maria made landfall over Puerto Rico in 2017 as a category 4 hurricane with wind speeds of up to 155 miles per hour. The storm resulted in a humanitarian crisis that brought into full view many of the islands existing social, political, and economic issues. The hurricane brought storm surge of up to 9 feet in parts of the coastline, exposing the vulnerabilities of the island's coastal communities and infrastructure. This impact highlights the urgent need to consider uncertainty related to sea level rise (SLR) and storm surge projections in future transportation planning, as well as the need to incorporate an equity perspective by considering vulnerable communities. The federal government has approved approximately \$20 billion to support recovery efforts. Allocations to the transportation sector have the potential to reshape the future of Puerto Rico's transportation systems and urban form. This applied research study explores multiple arenas that inform and influence transportation planning in this complex environment. The background and literature review synthesize the latest science on projections and uncertainty associated with SLR and storm surge and provide more context on the unique transportation challenges facing Puerto Rico. Subsequently, a desktop analysis is conducted in GIS to examine the exposure of both transportation assets and vulnerable communities to these coastal risks. The latest NOAA Lidar results are used in this analysis. In conjunction with findings from the literature review, the results of the desktop analysis inform recommendations for improving collaboration and consensus across jurisdictions and plans relevant to future transportation investments, with an emphasis on the effective use of federal expenditures post hurricane Maria.

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List of Acronyms

AASHTO	Association of State Highway and Transportation Officials
COP	Conference of Parties
DEM	Digital Elevation Model
EJ	Environmental Justice
EJSCREEN	Environmental Justice Mapping and Screening
EO	Executive Order
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FOMB	Financial Oversight and Management Board
FTA	Federal Transit Administration
GCM	Global Circulation Model
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GMSLR	Global Mean Sea Level Rise
HUD	Department of Housing and Urban Development
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
MOE	Margin of Error
MSJ	Municipality of San Juan
NCA4	Fourth National Climate Assessment
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Association
PROMESA	Puerto Rico Oversight, Management, and Economic Stability Act
RISE	Transportation Resilience Summit and Exchange
RPC	Representative Concentration Pathway
SCOTSEM	Special Committee on Transportation and Security and Emergency Management
SJMTA	San Juan Metropolitan Area
SLR	Sea Level Rise
TRB	Transportation Research Board
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
USDOT	United States Department of Transportation
USVI	United States Virgin Islands
VAST	Vulnerability Assessment Scoring Tool
WMO	World Meteorological Organization

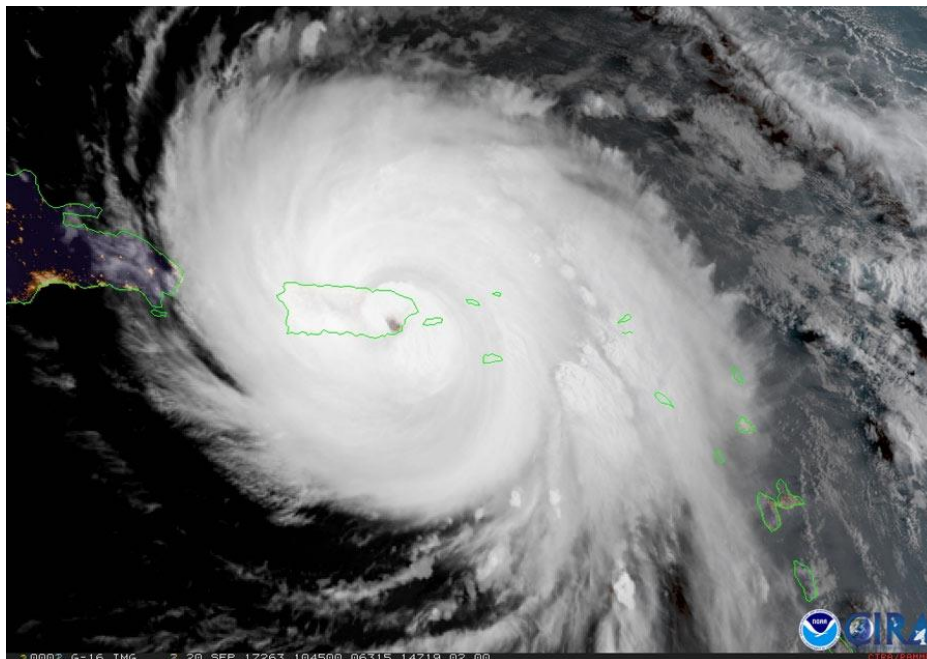
1. Introduction

The field of transportation planning is increasingly concerned with managing the impacts of climate change on critical infrastructure systems and the communities that depend upon them. Transportation systems are vulnerable to a number of climate stressors, from temperature swings, to flooding and extreme weather impacts. Coastal systems are particularly at risk to hazards like sea level rise (SLR) and impacts from extreme weather events, like storm surge during hurricanes. The Fourth National Climate Assessment (NCA4) estimates that over 60,000 miles of U.S. roads and bridges in coastal floodplains are already clearly at risk to impacts from storms and hurricanes, and that many coastal cities have begun experiencing increased high tide flooding due to SLR (Fleming et al., 2018). Communities across the nation are feeling the social and economic repercussions of coastal climate impacts, and there is an urgent need for coordinated adaptive planning and action to become a national priority.

The impact of hurricane Maria in Puerto Rico in 2017 throws into stark relief the extreme vulnerability of this U.S. territory, which is exacerbated by its island geography, political status, and an ongoing debt crisis. Since the passage of the storm, there have been a flurry of recovery planning efforts. In 2018, the U.S. Department of Housing and Urban Development (HUD) allocated approximately \$20 billion approved by Congress to support recovery and rebuilding efforts in Puerto Rico. HUD has approved an Action Plan to allocate approximately \$9.7 billion of this total so far, with approximately \$1.5 dedicated to infrastructure, including transportation (Government of Puerto Rico, 2019).

The federal allocations have the potential to reshape the future of Puerto Rico's transportation system. However, it is imperative that the government avoid rebuilding a system that 1) has proven to fail under stress from climate impacts and 2) has failed to provide adequate transportation service to the Puerto Rican population in the past. This paper makes the case that planners and decision makers across all levels of government should make a coordinated effort to integrate climate risk and uncertainty as well as equity into all documents relevant to transportation planning in Puerto Rico.

Figure 1: NOAA GOES-16 Satellite Image of Hurricane Maria over Puerto Rico, September 20, 2017



Source:
(NOAA, 2017)

Guiding Research Question:

In order to explore this topic in more detail, this paper explores the following research question:

What are the implications of sea level rise and storm surge on transportation planning in San Juan Metropolitan Area, Puerto Rico, specifically from an equity perspective?

Objectives:

To approach this question, this study focuses on four main objectives:

1. To conduct a background and literature review to understand uncertainty in SLR and surge projections, and the degree to which these are being considered in the complex post-disaster planning environment in Puerto Rico, with a focus on the transportation sector.
2. To conduct a basic, desktop analysis to examine the exposure of the road network and critical public transportation assets in the San Juan Metropolitan Area (SJMTA) to varying levels of SLR and storm surge scenarios possible in the 21st century.
3. To incorporate an equity perspective into the desktop analysis by also examining the sociodemographic characteristics of communities exposed to SLR and storm surge, with a focus on themes of socially vulnerability, environmental justice, and transportation disadvantaged communities.
4. To discuss implications of the findings from the literature review and desktop analysis for plans related to transportation in Puerto Rico, with an emphasis on the effective use of federal expenditures post Hurricane Maria.

These four objectives provide a framework that guides the structure of this paper.

2. Background and Literature Review

The first objective of this study is to conduct a background and literature review to understand uncertainty in SLR and surge projections, and the degree to which these are being considered in the complex post-disaster planning environment in Puerto Rico, with a focus on the transportation sector. To approach this objective, this literature review first explores the how climate science has evolved over time, and how the international community and the United States has come to consensus on the current state of knowledge. After a broad overview, the review summarizes key findings from the latest science on projections for SLR and storm surge.

Next the review examines how the transportation sector is reacting to the impacts of climate change, and efforts to integrate uncertainty related to climate risk into transportation planning. The study summarizes the legislative framework and guidance from the U.S. Department of Transportation (USDOT). The USDOT has initiated several programs and pilot studies under different branches. This study reviews three relevant case studies to inform methods for assessing the exposure of transportation assets to SLR and storm surge. The study then goes beyond understanding methods for analyzing exposure of assets. It expands to investigate the relationship between transportation assets and the communities that they serve, with a focus on equity.

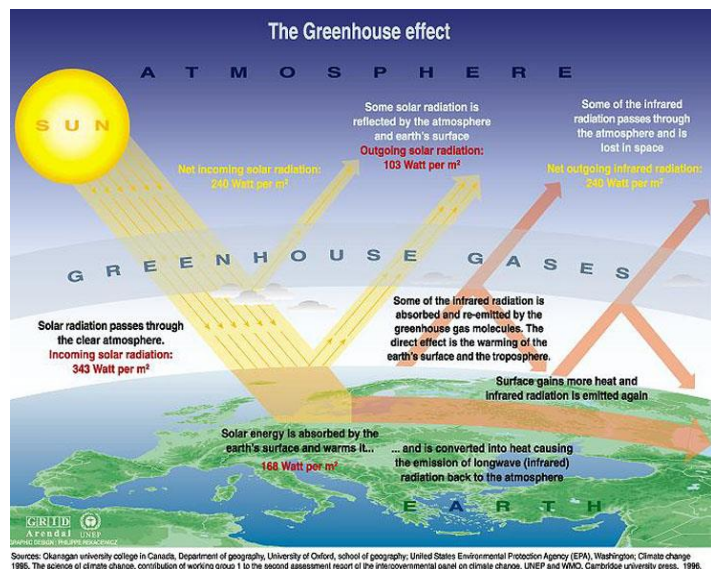
Finally, the literature review focuses on developing contextual knowledge on Puerto Rico. The study reviews the impact of hurricane Maria on the island, the political context, unique transportation challenges, and relevant plans and prior studies.

a. The State of Knowledge on Climate Change and SLR

Evolution of Climate Science

People have been actively studying changes in the earth's climate for centuries, but in the last thirty years the world has shifted towards a concerted global effort to study, understand, and disseminate information about climate change. In the 19th century during the throws of the industrial revolution, humans began unleashing enormous quantities of gases through activities like burning fossilized versions of CO₂ like coal, oil, gas, as well as forests. Theorists and scientists like Fourier, Tyndall, and Arrhenius began developing theories about the heat-trapping potential of gases in the atmosphere, otherwise known as the greenhouse gas effect. The greenhouse effect is described in Figure 2.

Figure 2: The Greenhouse Effect

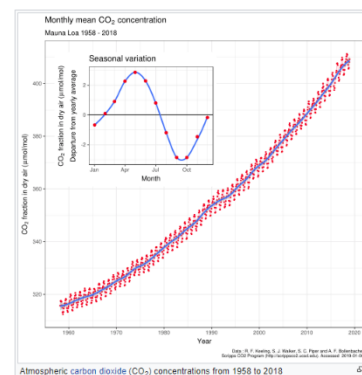


Source: IPCC, 1996

The effect occurs because most atmospheric gases are transparent and allow solar radiation (or light from the sun) to pass through the atmosphere until the rays hit the earth's surface. There, some of the solar energy is reflected straight back out through the atmosphere just as it came in. However, some of the radiation is absorbed by the earth's surface, warmed, and converted into heat which causes the emission of long-wave or infrared radiation back into the atmosphere. Long-wave radiation has more difficulty passing through the atmospheric gases, and some of it remains trapped, heating the atmosphere and Earth surface. Increasing the concentration of heat trapping gases in the atmosphere increases the greenhouse effect (Stone, 2012).

Methodological efforts to document changes in the earth's atmosphere began more formally in the 1950s when Charles Keeling installed one of the first devices to monitor atmospheric carbon dioxide in the atmosphere. Since the installation of his first instrument at the Mauna Loa Observatory in 1958, levels of CO₂ have grown from 315 parts per million (ppm) to 413.96 ppm today (Dillon, 2018), as shown in Figure 3.

Figure 3: The Keeling Curve



Source: Scripps CO₂ Program

Evolution of International Collaboration on Climate Change:

Establishment of the Intergovernmental Panel on Climate Change (IPCC), and the United Nations Convention Framework on Climate Change (UNFCCC)

Spurred by concerns over the potential adverse effects of increased concentrations of greenhouse gases, national and international efforts at understanding, mitigating, and adapting to climate change began to take form in the late 20th Century. In 1988, the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) created the Intergovernmental Panel on Climate Change (IPCC), which is the United Nations body responsible for assessing science related to climate change. The purpose of the IPCC is to provide “regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation” (IPCC, 2019). The IPCC is an organization of governments representing over 195 countries. IPCC scientists review the work of thousands of scientific papers to summarize the state of knowledge of the science on climate change. The organization synthesizes the information and describes the potential social and economic impacts, as well as possible response strategies that can be adopted at an international level or by individual countries.

The IPCC has three Working Groups and a Task Force which focus on 1) the physical science basis of climate change, 2) climate change impacts, adaptation, and vulnerability, and 3) mitigation of climate change. The Task Force is concerned with developing methodologies for reporting and reducing greenhouse gas emissions (IPCC, 2019). Overall, the IPCC represents a concerted international effort to develop consensus on the state of knowledge of climate change, and how to respond to potential impacts.

Since its creation in 1988, the IPCC has released five Assessment Reports, as well as numerous methodology reports, special reports, and technical papers. The First Assessment Report (FAR) was released in 1990. Concerned by the emissions projections predicted in the report, the United Nations began working on strategies to reach international agreements to stabilize and reduce emissions. Two years later, member countries adopted the United Nations Framework Convention on Climate Change (UNFCCC). This entity does not set emissions goals or have enforcement power, but rather it creates the framework for treaty development through annual meetings known as the Conference of Parties (COP). These conferences have been held annually since 1995 and assess the world’s progress in managing emissions and climate change (UNFCCC, 2019).

Landmark Treaties: Kyoto Protocol and the Paris Agreement:

Two landmark international treaties aimed at emissions reductions have resulted from the COP meetings over the past 25 years: the Kyoto Protocol and the Paris Agreements. However, commitments to these agreements have wavered over time and U.S. participation has been lacking. As such, the treaties have failed to reduce GHG emissions over this time, and emissions have been on the rise. Nevertheless, the treaties establish important precedents and innovative mechanisms for international collaboration (National Geographic, 2013).

The Kyoto Protocol was adopted in Kyoto, Japan in 1997, and signed by 150 countries. Over time, 192 countries have signed the Kyoto protocol, but notably, it has never been ratified by the United States. The lack of participation of the United States and the limited commitment of other large industrialized countries, has weakened the protocol which depends on market mechanisms and international collaboration.

The Kyoto Protocol establishes legally binding emissions reductions for member countries. However, it recognizes that developed countries are primarily responsible for the high levels of GHG emissions in the world due to processes of industrialization and growth. Given disparities in emissions by developed and developing countries, the protocol differentiates between the two: it establishes legally binding targets for developed, or 'annex' countries, while developing ('non-annex') countries are exempt. For example, the Solomon Islands are non-annex and do not have legally binding targets (UNFCCC, 2019).

The protocol commits industrialized countries to reducing emissions by a certain percentage during a specific timeframe. For example, phase 2 aims to reduce emissions by 18 percent below 1990 levels by 2020. A variety of market-based mechanisms are applicable to achieve this international collaboration, such as emissions trading between countries, credit swaps, and joint implementation. Joint implementation is a mechanism which allows developed countries to earn emission reduction units (equivalent to one ton of CO₂) by investing in CO₂ source reduction or an enhancement of carbon sinks (e.g.: reforestation) in a developing country. This flexibility permits technology transfer between developed and developing countries.

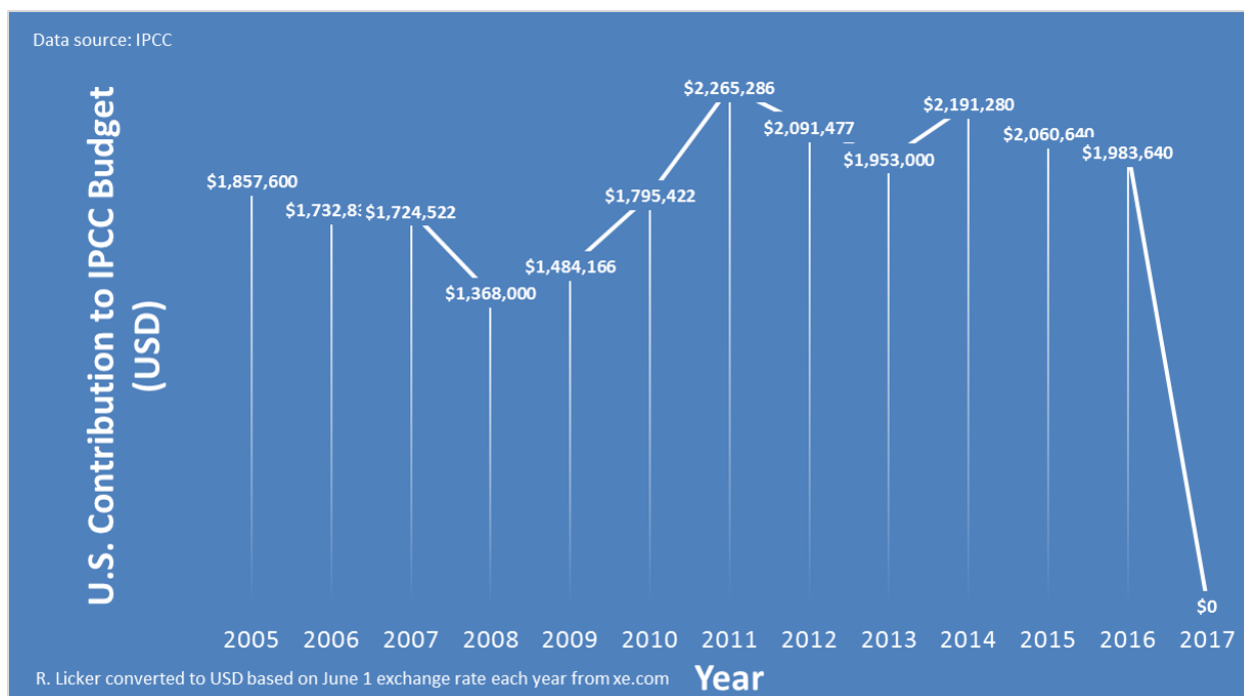
The second landmark international treaty was the Paris Agreement which resulted from the 21st Conference of Parties of the UNFCCC held in Paris in 2015. The agreement has been signed by 195 member countries including the United States under the Obama Administration. Recently, however, President Trump has stated his intention to withdraw the United States from the Paris Agreement, which would severely impact its credibility and effectiveness (Zhang, Dai, Lai, & Wang, 2017).

While the Kyoto Protocol focuses on specific emissions targets, the Paris Agreement tackles climate change from the perspective of impacts. It aims to keep the increase in global average temperatures to below 2°C (or 35.6°) above pre-industrial levels. Given the dangers posed by global warming of 2°C, the agreement further aims to limit warming to below 1.5°C (34.7°F). It requires that each country to develop *Nationally Determined Contributions* (NDCs) to mitigate global warming, and to regularly report on their progress. No targets or dates are specified, but each country's effort is expected to be ambitious and to progressively exceed prior agreements or stated ambitions over time. Beyond mitigating emissions and resulting global warming, the Paris accord also includes agreements to enhance transparency, improve adaptation mechanisms to deal with the impacts of climate change, reduce losses and damages associated with climate impacts, and strengthen the role of cities, regions and local authorities in contributing to the goals of the accord (European Commission, 2019). In this way, the Agreement shifts international collaboration into a new era where the focus combines mitigation and adaptation strategies and enhances the role of cities and local government in meeting global goals.

According to the stipulations of the Paris Agreement, President Trump's proposed withdrawal cannot occur until 2020, thereby hinging on the following presidential election in the United States. While the administration is abiding by these protocols, the United States intention to withdraw has upended traditional international alliances, caused shifts in the global balance of power, and undermined worldwide efforts to address climate change. While the United States is not yet formally out of the Paris Agreement, it pulled funding from international efforts to combat climate change. In a reversal of policy and place on the world stage, the Trump administration has exacerbated emissions contributions by sponsoring fossil-fuel extraction and coal-burning and aligned with the agendas of oil-producing countries such as Saudi Arabia. Furthermore, it has ceased implementing its Nationally Determined Contributions and financial contributions, including reducing its annual monetary contribution to the

IPCC to zero dollars, as shown in Figure 4 (Ekwurzel, 2017),(Zhang et al., 2017).

Figure 4: U.S Contributions to the IPCC Budget



Source: Ekwurzel, 2017

Climate Change Science – Current IPCC and National Assessment Reports

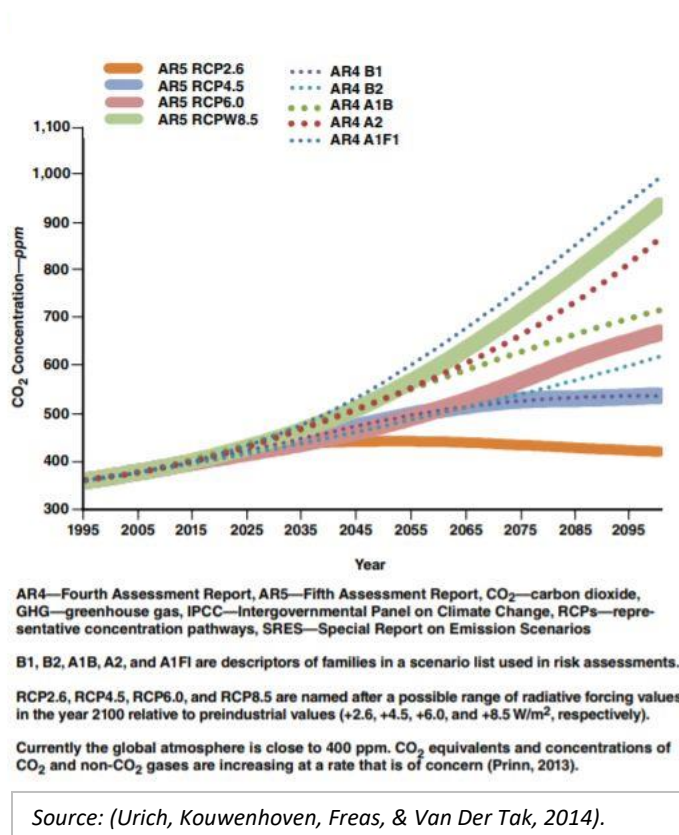
Despite the upheaval of the Paris Agreement and the withdrawal of U.S. commitment and funding to support climate change initiatives, research communities at both the international and national level have continued to produce reports establishing the latest consensus on climate science.

International Panel on Climate Change – Climate Assessment Reports

Since the release of the First Assessment Report (FAR) in 1990 that eventually spawned the UNFCCC and resulting international agreements, the IPCC has released four additional reports. The Fifth Assessment Report (AR5) of the IPCC was published in 2014. The sixth assessment cycle is underway, and the first special report has been released titled Global Warming of 1.5°C (SR15). This report, along with the output from AR5, are important references for this paper, as they constitute the latest international consensus on climate change science (IPCC, 2019).

These reports depend upon climate projections that result from an ‘ensemble’ of over 20 separate global circulation models (GCMs) that are run by independent groups. GCMs are a type of climate model designed to simulate the dynamics and processes of the atmospheres and oceans. The ensemble models must respond to a set of economic, population, and emissions assumptions known informally as ‘storylines’ and more formally as ‘Representative Concentration Pathways’ or RCPs. Four new storylines, or GHG concentration trajectories, were adopted by the IPCC for its AR5. These are reviewed in the tables and graphics below. RCP8.5 is considered the worst-case scenario, while RCP2.6 is the scenario projected if society can maintain CO₂ concentrations in the atmosphere at their current levels:

Figure 5: GhG Scenarios from IPCC AR4 and AR5 CO2 Concentration:



These storylines provide the baseline scenarios considered in the most recent IPCC reports. They constitute the range of uncertainty considered when projecting the impacts of GHG emissions. The storylines, however, are not without their criticisms, and they have been hotly contested in the literature and public arena. Some critics suggest that the IPCC places too much certainty in the Global Circulation Models that underpin the RCPs. They argue that these models cannot accurately represent all of the complexities of the earth, oceanic, and atmospheric processes. For example, Lupo & Kinonmonth study the GCMs and find limitations associated with the resolution of the models. Given limitations in computational power, GCMs must operate in low resolution. This results in the inability of the models to capture the finer grain details of processes occurring at the regional and local scale. The authors also argue that the

GCMs may fail to account for “multiplier effects” that could amplify certain impacts or processes. In addition, they find that the models have difficulty portraying current climate conditions, which reduces their reliability for predicting future conditions.

Despite these criticisms, advances in computational power, technology, and integration result in continual improvements to the model. The AR5 report notes that there has been significant improvement to understanding sea level rise change since the previous AR4 report. The language of the IPCC reports is also carefully calibrated to acknowledge degrees and levels of uncertainty. Despite uncertainty in the reports and limitations of the models, these projections are the best efforts and consensus of the global scientific community. To the extent possible, local jurisdictions must try to incorporate these findings and uncertainties into their plans. A failure to consider the risks may be extremely costly.

U.S. Global Change Research Program – National Climate Assessments

In addition to reports and initiatives at the international level, there are national level efforts to synthesize the science on climate change and describe implications for the United States. In 1990, Congress passed the Global Change Research Act that mandates that the U.S. Global Change Research Program (USGCRP) issue a report to Congress and the President every four years. In 2018, the USGCRP issued the Fourth National Climate Assessment Report (NCA4) compiled by 13 federal agencies. Over 300 federal and non-federal experts volunteered their time to produce this report, which involved collaboration and integration with findings from the IPCC.

The production and publication of this report is especially surprising given that it was released under the administration of President Trump, who has repeatedly denied climate science and taken measures to undermine this type of research. The report unequivocally describes how climate change is impacting the nation's communities, critical infrastructure systems, health, and economy, and describes how communities are attempting to reduce risks and enhance resilience. The report concludes that "the evidence of human-caused climate change is overwhelming and continues to strengthen, that the impacts of climate change are intensifying across the country, and that climate-related threats to Americans' physical, social, and economic well-being are rising" (USGCRP, 2018). The following section summarizes key findings from both the IPCC and NCA4 reports that discuss sea level rise and storm surge.

Relevant findings on Sea Level Rise and Storm Surge for Puerto Rico and the Caribbean Region

Sea Level Rise:

Chapter 5 of the IPCC AR5 report summarizes the latest science about Coastal Systems and Low-Lying areas. On a global level, the report finds that the main drivers of sea level rise include thermal expansion as the oceans warm, as well as water melting from the glaciers, icecaps, and ice sheets of Greenland and Antarctica. Under a low emission scenario (RCP 2.6), global mean SLR (GMSLR) is expected to be almost 1.5 feet by the end of the century (MOE: 0.91ft – 2ft). Under the highest emission scenario (RCP 8.5), mean global SLR is expected to be 2.4ft by 2100 (MOE: 1.7ft – 3.2ft). The following table adapted from IPCC summarizes the expected global mean SLR under different scenarios:

Emission Scenario	Representative Concentration Pathway (RCP)	2100 CO ₂ concentration (ppm)	Mean Sea Level Rise (feet)	
			2046-2065	2100
Low	2.6	421	0.79 [0.56 - 1.05]	1.44 [0.92 - 2.00]
Medium Low	4.5	538	0.85 [0.62 - 1.06]	1.74 [1.18 - 2.33]
Medium High	6	670	0.83 [0.59 - 1.05]	1.80 [1.25 - 2.40]
High	8.5	936	0.95 [0.72- 1.25]	2.43 [1.71 - 3.22]

Source: Adapted from IPCC AR5 (Wong, et al. 2014)

There is still a large amount of uncertainty around these projections and a probability of up to 33 percent that GMSLR will exceed these bounds. Other models based on past climates and ice-sheet dynamics have estimated GMSLR upper bound of up to 7.87 feet by 2100, though there is a lower degree of international consensus on these numbers. The Fourth National Climate Assessment (NCA4) similarly warns that rapid ice loss from Greenland and Antarctica could result in GMSLR of over 8 feet (Fleming et al., 2018).

Extreme SLR is possible through a combination of factors, including storm surge, wind waves and swell, and astronomical tides. The IPCC suggests that given the uncertainties, coastal risk managers must establish their own acceptable level of risk. For example, the Dutch Delta Programme is considering a GMSLR upper bound of 4.27ft for 2100 (Wong, et al. 2014).

Regional and Local Variability:

In addition to acknowledging the uncertainty and possibility of more extreme GMSLR, the IPCC emphasizes that there is considerable regional and local variability in the rate of SLR around the world. SLR rates may vary because of effects like the El Niño-Southern Oscillation, changes in air and wind pressure, storm surge, freshwater fluxes, ocean currents, and other dynamic ocean and climate processes.

Researchers have been maintaining independent measures of SLR in Puerto Rico and the USVI, which are summarized in the NCA4 Report, Chapter 20 which focuses on the U.S. Caribbean region. Measures show that relative SLR has risen on average 0.08 inches per year in Puerto Rico and the USVI. However, rates have been accelerating since the early 2000s. There has been a noticeable acceleration (by a factor of about 3) starting in 2010/2011. As such, this region has adopted projections of extreme SLR that are higher than the global mean. For 2100 under extreme scenarios (RCP 8.5), projections for SLR in the U.S. Caribbean range between 9 and 11 feet. Intermediate to low projections for the end of the century are between 1 and 2 feet, and intermediate projections are at 3-4 feet (Díaz et al., 2018, p. 20).

Further, there are anthropogenic influences on the rate of SLR that occur at the local scale. For example, cities built on river delta's, like New Orleans for example, are experiencing subsidence. Subsidence is the gradual sinking of the land, a natural phenomenon that can be exacerbated by compacted soils, the weight and density of built structures, reduced sediment delivery to the coast, and extraction of subsurface resources like petroleum, gas, and groundwater (Wong, et al. 2014).

Exacerbations by Storm Surge, Wind and Wave Action:

Severe storms, wind, and wave action can further exacerbate the effects of SLR. Storm surge and waves can cause coastal inundation, erosion, as well as accretion. There is a lower degree of international consensus on the trends and impacts of extreme storms due to a smaller number of studies, regional variation, and differences in the models, methods and findings across studies. However, the IPCC finds that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic (IPCC, 2013). While there is greater uncertainty in the future frequency of tropical cyclones globally, their intensity is likely to increase, as measured by precipitation rates and maximum wind speed (IPCC, 2013). The IPCC warns that low lying areas are at risk of extreme sea levels and inundations brought on by storms, wind and wave action. As such, this risk should factor into planning decisions.

b. Climate Change and the Transportation Sector

There are several initiatives at the national level to integrate climate science into transportation planning, engineering, operations, and asset management. Federal agencies and leading bodies in the transportation research community have developed guidance documents to help transportation professionals understand important concepts, frameworks, and strategies for adapting transportation infrastructure. This section summarizes the concepts and findings from guidance documents discovered in the literature review. Key resources include guidance documents produced by the U.S. Department of Transportation (DOT), subsidiary agencies and institutes to DOT like FHWA and FTA, the American

Association of State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB).

Analyzing Exposure of Transportation Assets:

DOT Legislative Framework, Guidance Documents, and Case Studies:

Two Executive Orders (EO) issued under the Obama Administration required action on the part of USDOT to prepare for the impacts of climate change on the nation's transportation infrastructure. While these EOs have since been revoked under the Trump Administration, they resulted in several important plans and guidance documents on transportation adaptation and climate change planning. In 2009, Obama signed EO 13514, titled "Federal Leadership in Environmental, Energy, and Economic Performance" (EO 13514, 2009). This EO required that the U.S. DOT submit a Climate Change Adaptation Plan in 2013, which included the DOT's Policy Statement on Climate Adaptation. The Adaptation Plan summarizes threats to the nation's transportation infrastructure and calls on agencies to integrate considerations of climate change in the building, operation, and maintenance of their assets. The Plan warns that these threats could shorten the life-cycle of critical transportation assets or render them obsolete. The Plan describes actions, tools, and guidance developed by their subsidiary agencies like the Federal Aviation Administration (FAA), the Federal Transit Administration (FTA), and the Federal Highway Administration (FHWA), among others (U.S. DOT, 2013).

The second relevant Executive Order signed by the Obama Administration is EO 13653: *Preparing the United States for the Impacts of Climate Change* (EO 13653, 2013). While this EO has also been revoked, it has similarly resulted in actions and orders for the U.S. DOT and its subsidiary agencies. For example, the EO resulted in FHWA Order 5520 titled *Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events*. The directive defines relevant concepts and terms, describes the FHWA's policy on climate change and preparedness and outlines the scope of the agency's authority and responsibilities. Order 5520 defines resilience as "...the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to and recover rapidly from disruptions" (FHWA Order 5520, 2014). While these Executive Orders have been revoked under the current administration, federal agencies continue to carry out the directives and orders.

Because of these Executive Orders, and in response to climatic events that have impacted transportation infrastructure, the U.S. DOT has carried out a series of pilot projects and developed numerous tools to facilitate climate change adaptation for transportation agencies. Three of these projects were selected for review given their relevance to the San Juan case study. Criteria for selecting these case studies include 1) their vulnerability to similar climate threats like SLR, hurricanes, and storm surge, 2) regions that have experienced impact from a major hurricane 3) studies that are sponsored by the USDOT and are of national significance, and 4) that they focus on developing frameworks, tools and strategies related to managing critical and vulnerable transportation infrastructure. The three case studies explored are 1) the South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project, 2) The Post-Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut, and 3) the Gulf Coast Study.

These studies are reviewed to determine methodologies applied in analyzing the vulnerability of transportation assets to climate change impacts, specifically SLR and storm surge. These studies adopt the FHWA's definition of vulnerability and its subcomponents for the analysis. Vulnerability is considered a function of Exposure, Sensitivity, and Adaptive Capacity, which are defined as follows:

- *“Exposure: The degree to which a transportation facility is subject to adverse climate changes”*
- *“Sensitivity: The capacity of an asset to deal with changes in a climate stressor”*
- *“Adaptive Capacity: The ability of the transportation network to deal with the loss of an impacted asset” (USDOT, 2015).*

In reviewing these studies, this review places emphasis on examining the indicators used to measure the exposure of assets to SLR and storm surge to inform methodologies for the desktop analysis of the San Juan Metropolitan Area.

South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project

Southeast Florida is one of the most exposed regions in the country to climate impacts like sea level rise, storms, storm surge, and flooding. The region has been extensively damaged by recent hurricanes, such as Hurricane Mathew in 2016, and Irma in 2017. Sea level rise is a major threat to the low-lying region. In 2009, elected officials of four counties came together at the Florida Climate Leadership Summit, and discussed strategies for jointly responding to the threats of climate change. As a result of this meeting, they formed the Southeast Florida Regional Climate Compact (Compact), which is a bipartisan agreement representing the Broward, Miami-Dade, Monroe, and Palm Beach counties. The Compact is responsible for fostering regional cooperation and facilitating collaboration with state and federal partners who provide technical support (SFRCCC, 2019).

In 2013, the region was selected as one of the FHWA's sponsored climate resilience pilot projects. The purpose of these pilot studies was to “conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency” (USDOT, 2015). In the pilot project, the Compact applied the FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework. Their study focused on road and rail transportation networks and assessed their vulnerability to three climate stressors associated with flooding, including sea level rise, storm surge, and heavy rainfall.

The study further defined the data inputs required for each element of vulnerability, to serve as inputs for the overall scoring:

Sensitivity: The sensitivity measure takes into the account the current condition of the asset. For this study, the sensitivity index was limited to determining the number of bridges on a road segment, and the condition of the bridges as determined by the National Bridge Inventory. Specifically, scour condition rating and substructure condition ratings were incorporated into the index. Sensitivity indices were only developed for the roads, as similar data was not available for rail.

Exposure: For exposure, the study differentiates between flooding that is permanent as a result of SLR, and periodic flooding that is caused by storms and precipitation events. Exposure to SLR and periodic flooding required technical interventions to ensure consistent interpretation across the region. For SLR, the Compact had to reconcile datasets and maps generated by the different agencies. In order to achieve this, the Compact created a mosaic of the most high-resolution LIDAR datasets available, and rectified the maps to achieve a standard, regionally coherent estimate of flood risk. They also rectified the maps to ensure that structures like bridges were not portrayed as flooding, by accounting for the elevation of the bridge deck. Once the maps were rectified, the SLR inundation layers were overlaid onto the road network.

In addition to exposure to permanent inundation by SLR, the exposure measure also included two indices related to periodic flooding from storms and precipitation. One index measured current exposure, while the second calculated future or projected exposure. Current exposure was measured by intersecting the road and rail networks with rectified 100-year flood zone maps obtained from the FEMA National Flood Hazard Layer. Two elements were multiplied to obtain this index: the percent of the segment inundated, and the average depth of inundation (used as a proxy for the severity of flooding).

The second index of future or projected exposure was calculated based on the assumption that assets at risk are those near to the 100- year flood plain and with little or no elevation difference. Thus, the index was derived by measuring the distance of the asset to the nearest FEMA 100-year flood zone, and the difference in elevation to the flood zone. These measures were weighted and summed to achieve the index.

Adaptive Capacity: Adaptive capacity was a combined measure of the volume and detour lengths around segments. Volume along roads was measured by average annual daily traffic (AADT) along each segment, while for rail it was a measure of annual ridership for 2013 for each segment. “Detour lengths were calculated by finding the shortest path around the segment of interest under the assumption that detours had to follow other regional network (i.e. major) roads.” The indicator of adaptive capacity for rail was measured by ridership.

Scoring and weighting: After creating each of the indices, the study developed a scoring and weighting system for each index, which were then rolled into one overall vulnerability score that ranged from 0 to 100, with 100 being the most vulnerable. Scoring ranges were developed on a scale of 0 – 100 for each individual index to standardize them. Weights were also applied to each index to indicate their relative importance in the overall vulnerability index. Sensitivity was given a weight of 20 percent, while exposure was given the highest weight at 70 percent, and adaptive capacity the lowest weight at 10 percent. Authors justified giving the exposure index a much higher weighting than the other indexes by explaining that it is considered a threshold factor; in other words, without the risk of exposure, sensitivity and adaptive capacity are not considered important (USDOT, 2015).

Results: The results of the analysis helped develop maps where vulnerability, as a function of exposure, sensitivity, and adaptive capacity, could be visualized. The study identifies highly vulnerable road and rail facilities, which enabled authors to more clearly define focused adaptation strategies and tie the results to specific decision-making processes and policies.

The Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT:

Hurricane Sandy made landfall in the Northeast United States in the fall of 2012 and caused massive destruction and loss of life. An estimated 150 people were killed in the mainland U.S., and the costly storm inflicted an estimated \$70 billion in damages (Gibbens, 2019). The *Post-Hurricane Sandy Transportation Resiliency Study* was led by the FHWA with the intent to improve the resiliency of the transportation system in the tri-state area of New York, New Jersey, and Connecticut. The study took place between 2013 and 2017. At the highest level, the study team conducted a vulnerability assessment to determine the potential exposure of transportation assets to climate stressors. Next the study conducted more detailed assessments of subareas, and finally it focused on 10 different transportation assets to carry out facility-level analysis and propose design and engineering solutions (Adaptation Clearinghouse, 2019).

For the exposure component of their regional vulnerability assessment, this study team assessed two factors: 1) storm surge with and without SLR, and 2) precipitation. To determine exposure, the study used intersection analysis in GIS to identify where roads, rail lines, and facilities lie within the boundaries of the 100-year and 500-year flood plain, or within the extent of storm surge predicted to be associated with Category 1 through 4 storms. For data sources, they relied on the U.S. Army Corps of Engineers results from the North Atlantic Coast Comprehensive Study (NACCS) for data on SLR and storm surge, using projections for years 2068 and 2100. The study also used outputs from a *Sea, Lake, and Overland Surges from Hurricanes* (SLOSH) model developed for the NACCS. The study also used FEMA's National Flood Hazard Layer to determine the extent of the 100 and 500-year floodplains.

Gulf Coast Study:

The Gulf Coast is another region that is exposed to coastal climate threats, and it has experienced extensive damage from numerous hurricanes like Katrina in 2005, and Harvey in 2017. The region has many vulnerable transportation assets. The U.S. DOT describes the Gulf Coast study as a “comprehensive, multi-phase study of climate change impacts in the Central Gulf Coast region...to better understand potential climate change impacts and identify adaption strategies” (FHWA, 2019). The study is sponsored by the U.S. DOT's Center for Climate Change and Environmental Forecasting as well as the U.S. Geological Survey and managed by FHWA.

The U.S. DOT focused resources on the Gulf Coast region because of the large variety of transportation assets in the area, the economic importance of the region in importing, exporting, and transporting goods, the populations centers, and its vulnerability to climate impacts. The study was composed of two parts, the first which was completed in 2008 and examined the area at a regional scale to understand risks to coastal ports, road, air, rail and public transit systems. The second phase, completed in 2015, was a more focused investigating the Mobile, Alabama region. The reduced scale allowed researchers to focus on developing tools to enhance the capacity of decision-makers to identify critical assets, assess their risk to potential climate impacts, and consider options for adaptation. By focusing on one specific region, U.S. DOT intended to develop decision support tools that could be applied elsewhere: “The methods and tools developed under Phase 2 are intended to be replicable through the country” (FHWA, 2019).

One of the tools that emerged from this study is the Vulnerability Assessment Scoring Tool (VAST). The Excel spreadsheet based-tool guides users through a quantitative, indicator-based vulnerability screen. The tool was applied in Mobile Alabama to evaluate the impacts of climate change on highways, ports, airports, rail, transit, and pipeline infrastructure. SLR, storm surge, and winds associated with intense storms were among the climate stressors included in the study. For the SLR indicator, the study used projections of 1ft of GMSLR by 2050, and a range between 2.5 ft and 6.6 feet by 2100. For storm surge and wind scenarios, the project team analyzed 11 storm scenarios based on historical storms. With this information they developed an Advanced Circulation (ADCIRC) for storm surge and a separate model to simulate wave action.

FHWA Vulnerability Assessment and Adaptation Framework

Building from these case studies and other pilot studies, the FHWA has since developed a *Vulnerability Assessment and Adaptation Framework* which provides guidance and methods for approaching the complex tasks of analyzing risk and adapting systems to the challenges of climate change. This evolving framework compiles lessons learned from the literature and experiences around the country,

incorporating best practices, tools, and resources. This paper experiments with applying tools and concepts extracted from the Framework in the San Juan Metropolitan Region in Puerto Rico, as well as applying the methods for measuring exposure. While the desktop analysis for this paper cannot be as sophisticated as these other studies, the basic concepts are used as guidance for the methodology.

AASHTO and TRB guidance on adaptation and resiliency:

In addition to resources and initiatives under the U.S. DOT, other widely respected non-governmental organizations have developed their own guidance on transportation, adaptation, and resiliency. This section explores the contributions of two major non-profit organizations that are important to the transportation industry, namely the American Association of State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB).

In 2017, AASHTO published a report titled *Understanding Transportation Resilience: A 2016-2018 Roadmap* (AASHTO, 2017). The study was conducted as part of the National Cooperative Highway Research Program (NCHRP), whose funding comes from the voluntary contributions of state Departments of Transportation (DOTs). The project support AASHTO's Special Committee on Transportation and Security and Emergency Management (SCOTSEM) whose mission is to serve state DOTs, AASHTO committees, and related partners to enhance resilience programs. The document adopts the definition of resiliency as stated by the National Academy of Sciences, Engineering and Medicines: "resilience is the ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events" (AASHTO, 2017, quoting NASEM).

The committee approaches the discussion of transportation resiliency from the perspective of security, emergency, and infrastructure protection. It proposes and defines several strategies to achieve resiliency, including adding redundancy to the system such as backup components, allowing for components to be substituted, reducing vulnerabilities, improvising approaches, prioritizing access to critical resources, pre-emptively modeling disruptions, and planning backup logistics. In addition to these strategies, they suggest a framework for continuous and evolving research on resiliency based on cross-jurisdictional and cross-institutional collaboration, involving the sharing of knowledge, skills, and lessons learned from experience (AASHTO, 2017).

AASHTO collaborates with other committees and initiatives like those of the TRB to advance research on pressing issues. TRB is one of seven major programs of the National Academies of Sciences, Engineering and Medicine. The organization engages about 7,000 engineers, practitioners, researchers, and transportation professionals annually. In 2015, TRB established the Transportation Systems Resilience Section which includes three committees: Critical Transportation Infrastructure Protection, Logistics of Disaster Response and Business Continuity, and Emergency Evacuation. In 2017 these committees released a report on *Transportations Systems Resiliency* with a focus on preparation, recovery, and adaptation. The report discusses the need for an integrated, whole-system approach to resilience in transportation systems, as well as the need to consider key elements like the cyber-physical connection, and employee training (Dougherty, Turnbull, Hanson, & Pederson, 2017).

TRB hosts conferences on an annual basis. In addition to the annual national conference in Washington D.C., in 2018 TRB hosted the Transportation Resilience Summit and Exchange (RISE). This event convened all 50 State DOTs to exchange information about resiliency programs and initiatives, with a focus on enhancing organizational capacity, recognizing infrastructure dependencies, fostering partnerships, and making the case for resiliency (TRB, 2018).

One of the ‘Hot Topics’ in the subject tracks at the TRB annual conference in D.C. in 2019 was ‘Resilience and Sustainability.’ Within this track, there were several sessions that discussed priority research needs at a national level. One of these sessions served as a follow up the 2018 RISE conference. At this lectern, representatives of the AASHTO SCOTSEM discussed how this committee was seeking a more strategic approach to projects funded by the NCHRP, which has a \$22-25 million budget oriented towards the theme of transportation resiliency. The top-rated project concepts for this funding pot were listed as the following:

1. Integrating Resilience into Transportation Project Development
2. Economic Benefits from Making Investments in Resilient Transportation Assets
3. Design Guidance and Standards for Resilience
4. Assessing and Managing the Vulnerability of Transportation Assets
5. Incorporating Resilience in National Programs
6. Streamlining the Damage Assessment Process
7. Funding Resilience Adaptation
8. Using Improved Hydrological Forecasting to Improve Transportation Resilience
9. Resilience Performance Measures: A Quantitative Approach
10. Cyber Risk Transfer Strategies (Fletcher, 2019).

According to conference proceedings, SCOTSEM developed these priorities principally through review of the literature and expert knowledge. This current study is relevant to several of the national research priorities identified by AASHTO SCOTSEM.

In addition to the priorities presented by AASHTO’s SCOTSEM, TRB’s Special Task Force on Climate also presented the five research priorities they have identified, mainly through conversations with practitioners. According to conference proceedings, practitioners ranked these research priorities as having the highest potential for return on investment. These included:

1. Making a business case for adaptation investments
2. When to stop shielding assets and relocate them
3. Understanding and communicating risk
4. Facilitating agile and flexible infrastructure for a changing climate
5. Understanding the environmental impacts of adaptation investments (Graff, 2019).

This content of this paper is relevant for these categories. It is noteworthy that there are competing research priorities brought forth by different groups, and in the discussions that followed, there were comments for a need to coalesce around a common research agenda. At the same time, given the rapid and changing pace of the climate, it is likely that these priorities will be in constant evolution. These conversations reflect the complexity of defining a single path forward for research priorities, and perhaps make the case for “muddling through” priorities as they bubble up from different sectors and stakeholders (Lindblom, 1959).

In addition to the sessions on national priorities by AASHTO and TRB, another session at the annual conference provided guidance and inspiration for this paper. The workshop was led by the U.S. Army Corps of Engineers (USACE) Risk and Decision Science team, and focused on *Methods in Resiliency Quantification* (Linkov, 2019). A component of the workshop focused on the application of network science to quantify the efficiency and resiliency of road networks. Presenters distinguished between the

concepts of efficiency and resiliency, emphasizing that most transportation models have been built to reduce inefficiencies in transportation systems under normal conditions, by reducing delays and congestion. Only more recently has research begun to incorporate themes of resiliency, or the modeling of transportation systems under disruptive conditions. The authors emphasize the need for more advances in what they described as the “emerging field of resiliency quantification” (Linkov, 2019).

Quantifying resiliency in transportation systems is difficult given the complex nature of our systems today, and their inter-dependence with other systems like communication and power networks, for example. Disruptions to one sector or segment of the system may have cascading effects that ripple throughout the system (Barami, 2013). As such, in order to advance the science of resilience quantification, Linkov Et al. recommend that research projects be clear in defining their scope and limitations. Specifically, studies should define the limits of the system (e.g. geographic scope, system type) and determine the key threats (e.g., terrorism, climate change). Researchers should also identify segments of the system that are critical to its functionality, and develop performance metrics (Linkov, 2019).

The recommendations of limiting scope and reducing complexity in the analysis of these problems is reflected in the FHWA Adaptation Framework and tools, which provide guidance and methods for focusing these types of studies. The first step in the framework is to articulate objectives and define the study scope.

Key takeaway from Case Studies, Federal, and Guidance documents for this study:

The review of the literature, case studies, conference proceedings, and current federal guidance has revealed that assessing the impact of climate change on transportation assets is highly complex and there are many competing priorities from different stakeholders. Successful assessments require the clear articulation of goals and objectives, identifying the audience for the study, and determining a manageable study scope. This study applies these lessons to help guide the scope.

So far, the scope of the study is effective in informing to objectives 1 and 2 of this study. The literature reviewed so far helps inform how to conduct desktop analysis to examine the exposure of the road network and critical public transportation assets in the San Juan Metropolitan Area (SJMTA) to varying levels of SLR and storm surge scenarios possible in the 21st century. However, examining at-risk transportation assets in isolation from the communities that they intend to serve is not conducive to effective planning. As mentioned in the introduction, a third objective for the current study is to incorporate an equity perspective into the desktop analysis by also examining the sociodemographic characteristics of communities exposed to SLR and storm surge, with a focus on themes of socially vulnerability, environmental justice, and transportation disadvantaged communities. To approach this objective, the next section of this literature review explores methods for incorporating these equity considerations.

c. Incorporating considerations of social vulnerability, environmental justice, and transportation disadvantaged populations

Hazards and social vulnerability:

In the field of disaster mitigation, recovery, and resilience, the literature has exposed a need for more research to focus on the connection between risk to physical assets and the social and economic impacts that could result from damage. By incorporating analysis of communities into the study, this paper expands the risk and vulnerability assessment beyond critical assets to also explore the exposure and sensitivity of the communities at risk to SLR. This allows critical infrastructure asset management to be further examined from an equity perspective.

Typically, in the past, hazards research has been dominated by physical scientists and engineers (Mileti, 1999). Nevertheless, more recently the literature has blossomed on the social dimensions of disasters and the impacts of climate change. One of the first pioneering reviews was by White and Haas in their work *Assessment of the Research on Natural Hazards* published in 1975. One of the major findings from the study is that “the all-important social, economic and political ‘people’ factors involved in hazards reduction have been largely ignored” (White & Haas, 1975). Haas and White argue for a national research agenda aimed at curbing losses by investing more in social sciences research focused on hazard mitigation. In addition, Haas and White suggest that the nation can apply policies, planning, and land use controls to better mitigate against disasters, instead of just responding to them (Mileti, 1999). These findings underscore the importance of the field of planning in hazards reduction and mitigating the impact of climate change.

Following the White & Haas publication, new disciplines have become engaged in research on hazards reduction and they have echoed the need for continued exploration of the social dimensions of hazards. For example, in his exploration of the topic of earthquake damages, French et al. from the field of City and Regional Planning argue that “to make rational decisions about investments in mitigation or disaster preparedness, decision makers need to understand not just the physical impacts of natural disasters, but also their likely social and economic consequences” (French, Lee, & Anderson, 2010). French et al. discusses social vulnerability, and how certain populations suffer disproportionate social and economic impacts from hazards, which can separate families, disrupt the social fabric of neighborhoods, and displace entire communities. Specifically, he points out that “individuals and groups with special socioeconomic characteristics, such as the poor, the elderly, children, women, renters, and ethnical minorities have been differentially impacted by natural disasters” (French et al., 2010). French emphasizes that vulnerability is not just defined by exposure to the disaster or climactic event, but by the pre-existing social, economic, and political conditions of populations before the event occurs.

French builds upon a body of hazard literature that discusses how certain populations are particularly vulnerable to the disaster or climate impacts. For example, Peacock, Morrow & Gladwin wrote a volume on the impact of Hurricane Andrew in Miami, discussing the sociology of disasters and how certain genders and ethnicities are more likely to be affected than others. They describe how “disasters are inherently social events. The nature of our communities – how they are organized....is a critical factor for understanding disaster impact and recovery” (Peacock, Morrow, & Gladwin, 1997). In this volume, the authors pay close attention to the impacts of the hurricane on minorities, women, and families in Miami. They explore the socio-economic history of the city before the hurricane, and through this lens

explore the impact of the hurricane on various sub-populations. In their findings, they discuss “the neglect of gender in disaster research,” and suggest a research agenda and policy considerations that are more gender inclusive.

Almost a quarter century after the White and Haas publication, Mileti carried out another comprehensive study in his volume *Disasters by Design: A Reassessment of Natural Hazards in the United States* (1999). In this volume, Mileti explores how the literature has evolved since the White & Haas 1975 publication. Mileti finds that a whole range of new disciplines has become engaged in the subject of hazards reduction. His assessment draws and expands upon this evolving body of literature. It contains an overview of losses, costs and impacts estimated from hazards throughout the U.S. over the past quarter century, and explains these losses as a function of three categories: “1) the influences exerted by the physical environment, 2) how human systems create and redistribute hazards, and 3) hazards that result from the nature of the constructed environment” (Mileti, 1999).

Expanding his research on the human systems, Mileti describes the concept of social vulnerability as it relates to hazards, or the “perspective that certain people experience socially created vulnerability—an elevated probability of loss, injury, death, and/or reduced ability to recover from hazards or disasters that is due to a range of social, political, and economic processes...” Like prior authors, he concludes that “the key characteristics that seem to influence disaster vulnerability most are socioeconomic status, gender, and race or ethnicity” (Mileti, 1999). These populations are more likely to reside in places that are subject to impacts of natural disasters, as well as built environments that are more dangerous when these disasters strike. A possible topic of future research to substantiate this study would be to further investigate rates of morbidity by hazard by sociodemographic characteristics.

Environmental Justice

The above review of hazards and social vulnerability makes the case that the impact of climate change and natural hazards are inherently issues of environmental justice, as certain populations are more susceptible to hardship than others. Environmental justice is a concept that has emerged over the last half century and made its way into the policy arena and the law. The U.S. Environmental Protection Agency (EPA) defines environmental justice as follows:

“Environmental Justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. ... Fair treatment means that *no group of people should bear a disproportionate share of the negative environmental consequences* resulting from industrial, governmental and commercial operations or policies.”
(U.S. EPA, 2016)

The concept of Environmental Justice began to make its way formally into law after EPA issued a 1992 report on Environmental Equity, which documented how some racial and income groups suffer health and exposure disparities compared to other groups. Two years later, the U.S. government passed Executive Order 12898 which mandated that each federal agency incorporate the concept of environmental justice as part of its mission to reduce adverse effects of its policies, programs, and activities on certain groups.

Despite progress, the topic of environmental justice has become highly politicized in the United States. Special interest groups, often related to non-renewable energy sector such as coal and oil lobbyists, have sought to dismantle EPA Environmental Justice programs and policies, which they see as counter to

their interests and burdensome to economic growth. In fact, one of President Trump's major campaign platforms in 2016 was to eliminate the EPA entirely as part of his plan to balance the budget (Feldscher, 2016). While he did not succeed at eliminating the agency, he has managed to severely weaken it by appointing heads-of-agency bent on dismantling the EPA from the top down. His first appointee was Mr. Scott Pruitt, a former attorney general who had formerly built his career on developing lawsuits against the agency. As head of EPA, Mr. Pruitt began "the largest regulatory rollback in the agency's history." Mr. Pruitt was forced to resign under a cloud of ethics scandals, and has since been replaced by Andrew Wheeler, a former coal lobbyist (Davenport, Friedman, & Haberman, 2018).

Despite efforts to dismantle and weaken the EPA, the agency continues to operate and manage Environmental Justice related programs largely thanks to the dedicated efforts of stalwart career employees. One such program is the Environmental Justice Mapping and Screening tool, otherwise known as EJSCREEN. Development of the EJSCREEN began in 2010, and it has undergone several revisions. It is a tool that compiles detailed demographic data across the nation at the Census Block Group level, which can be overlaid with a variety of environmental indicators to better understand the exposure of certain groups to environmental hazards. The national dataset compiled under the EJSCREEN allows for easier comparison across different regions. It provides standard reports that pull together environmental and demographic data to form a number of environmental justice indexes.

Currently, the EJSCREEN has two major demographic indexes and 11 different environmental indexes. The demographic indexes allow the user to quickly screen for populations that might be more vulnerable or susceptible to environmental justice issues. The first index includes just two populations, low-income and minority, defined as follows:

1. "Low-Income: The number or percent of a block group's population in households where the household income is less than or equal to twice the federal "poverty level."
2. Minority: The number or percent of individuals in a block group who list their racial status as a race other than white alone and/or list their ethnicity as Hispanic or Latino. That is, all people other than non-Hispanic white-alone individuals. The word "alone" in this case indicates that the person is of a single race, since multiracial individuals are tabulated in another category – a non-Hispanic individual who is half white and half American Indian would be counted as a minority by this definition."

The second index is a bit more robust in that it includes an additional four factors:

3. "Less than high school education: The number or percent of people age 25 or older in a block group whose education is short of a high school diploma.
 4. Linguistic isolation: The number or percent of people in a block group living in linguistically isolated households. A household in which all members age 14 years and over speak a non-English language and also speak English less than "very well" (have difficulty with English) is linguistically isolated.
 5. Individuals under age 5: The number or percent of people in a block group under the age of 5.
 6. Individuals over age 64: The number or percent of people in a block group over the age of 64."
- (U.S. EPA, 2016)

In order to roll these characteristics into a single index for these 6 indicators, the EPA uses the following formula:

$$\text{Demographic Index} = (\% \text{ minority} + \% \text{ low-income} + \% \text{ less than high school education} + \% \text{ linguistic isolation} + \% \text{ under age 5} + \% \text{ percent over age 64}) / 6$$

In addition to the demographic indexes, the EPA has developed 11 environmental indexes. These include measures such as air toxins cancer risk, exposure to ozone, diesel, lead paint, particulate matter, traffic proximity and volume, proximity to toxic waste facilities and water discharges, for example.

In the context of the present study, the EJSCREEN provides an interesting baseline from which to consider examining the impacts of climate hazards on populations from an environmental justice perspective to meet Objective 3, which then may have implications Objective 4, which is to inform for plans related to the transportation sector in the San Juan Metropolitan Area. However, several questions emerge about limitations the EJSCREEN, which raise the possibility of enhancing the tool to better suit the geographic and thematic focus of this study.

First, the 6-indicator demographic index may need to be adjusted to better distinguish vulnerable populations in Puerto Rico. Specifically, the definitions associated with indicators 2 (minority) and 4 (linguistic isolation) may not be as useful in the context of Puerto Rico. Regarding the minority definition, most everyone might be considered a non-white minority because of their Latino heritage. Regarding linguistic isolation, people who do not speak English may not experience linguistic isolation because the dominant language in Puerto Rico is Spanish. Given these potential caveats, it is necessary to first map and examine these indicators in Puerto Rico to test their relevance, and also consider other indicators that may be more appropriate. This study explores the EJSCREEN demographic index in the context of the San Juan Metropolitan Area to determine what variables are relevant in this context. Further, it goes on to incorporate new variables that are more context-specific, and experiments with rolling these into a new index.

A second consideration is that none of the 11 environmental indicators developed by the EPA consider the impacts of climate change. While developing a comprehensive index based on exposure to SLR and storm surge is beyond the scope of this study, it provides a start by overlaying areas exposed to SLR and storm surge on top of the demographic characteristics identifying vulnerable populations. Future research could attempt to develop a more sophisticated index based on the EPA model, whereby factors like degree, percent, or proximity to exposure are quantified.

Considering Transit-Dependent Populations

Beyond exploring populations that may be particularly vulnerable to the impacts of climate change, it is important for the purpose of this study to distinguish populations that are dependent on public transportation services. In this way, when making policy and planning recommendations for managing transportation assets, decision-makers can consider the spatial distribution of transit-dependent populations.

The literature is surprisingly thin when it comes to describing and defining transit-dependent populations: One author writes that: “there is a lack of research on the ‘transit-dependent’ population and how it is affected by transit policies” (Dill & Bates, 2013). At the same time, there is a large body of work focused on understanding characteristics that drive transit ridership, as well as transportation-

disadvantaged populations. While these studies have a somewhat different approach, they provide valuable insight on some of the demographic characteristics that explain transit-demand, while controlling for other contextual variables.

An important resource is a report by the Federal Transit Administration on *Transportation Needs of Disadvantaged Populations: Where, When, and How?* (Zhao & Gustafson, 2013). This report refers to transportation disadvantaged populations as persons with disabilities, older adults, or the poor. These groups are described as having fewer mobility options than the average population. The report also discusses other factors that impact transit use, such as land-use patterns (e.g.: sprawl), availability of affordable housing, spatial mismatch of jobs and residences, community design, vehicle ownership, age, obesity, gasoline prices, and quality of transit services.

Examining all of these factors is beyond the scope of this study, however a few demographic characteristics were selected to compliment the EJSCREEN indicators. Specifically, this study examines the following characteristics: 1) Households with no-vehicle available, 2) Travel time to work.

d. Puerto Rico: Background, Challenges, and Relevant Plans and Studies

Impact of the 2017 Hurricane Season and Political Context:

During the hurricane season of 2017, Puerto Rico experienced widespread devastation by two powerful hurricanes. Hurricane Irma passed just north of the island as a Category 5 storm on September 6th, killing at least three people and leaving over a million without power (Johnson, Arkin, Cumming, & Karins, 2017). Within the span of a few weeks, on September 20th, 2017, Hurricane María made direct landfall on the island as a Category 4 hurricane. The eye traced a diagonal path across the island from the southeast to the northwest corner. NOAA recorded windspeeds of up to 155 miles per hour. According to USGS and the National Hurricane Center, storm surge levels reached up to 9 feet in coastal areas (Government of Puerto Rico, 2019). The hurricane caused catastrophic damage across the island, impacting all sectors and causing a collapse of critical infrastructure systems. This included a complete shutdown of the power and communications grid, disruption to transportation systems including airports, ports, and the road network, and interruptions of food and water supplies. The hurricane halted all economic activity on the island and paralyzed the government.

While originally the official death toll was reported at 64, later studies, such as one released by the Milken Institute School of Public Health at George Washington University, raised questions about these estimates and put the death toll at 2,975, numbers that were then adopted by Puerto Rico Governor Roselló (Brindley, 2018). Lack of access to clean drinking water resulted in an outbreak of Leptospirosis, a bacterial illness which spreads through water and soil. At least 26 people died from Leptospirosis, according to a joint investigation by CNN and the Center for Investigative Journalism in Puerto Rico (Sutter, 2018).

Damages across the island are estimated at \$94 billion (Government of Puerto Rico, 2019). Over 1 million homes experienced damages. The hurricane resulted in the largest and longest blackout in U.S. history (Houser & Marsters, 2018). It took nearly a year to restore power across the island (Sullivan, 2018). An After Action Report released by FEMA documents failures and a botched government response to the humanitarian crisis. FEMA Administrator William Long included a letter in the report

calling on emergency managers at all levels of government to coordinate to improve emergency plans to avoid logistical breakdowns for future disasters, and communities to be better prepared for emergencies. He warned that “These disasters demonstrate that our current organizing structures are insufficient to promote this collaboration” (Hernandez, 2018). His statement underscores the need to better understand community and infrastructure interdependencies for improved disaster mitigation and recovery.

Hurricane María exacerbates and brings to light existing problems on the island. Prior to the impact of Hurricane María, unemployment was at 11 percent, and over 40 percent of the population was living under the poverty line, which is more than triple the rates of poverty on the mainland USA (Government of Puerto Rico, 2019). As the vegetation was stripped away by the hurricane, these problems became more visible. Hurricane María further revealed the extent of severe poverty and inequality across the island, symptoms of larger economic and political problems.

Before the hurricane, the island was in the midst of negotiating how to manage \$74 billion in public debt that it has accrued over the past several decades. To manage the debt, the U.S. government passed the Puerto Rico Oversight, Management, and Economic Stability Act (PROMESA) in 2016, which established a Financial Oversight and Management Board (FOMB) charged with restructuring the island’s debt. There is controversy over the role of this entity, given that members are appointed by the President of the United States, which residents of the territory are not allowed to vote for. There are also potential conflicts of interest within the board. For example, two members of the board, Carlos M. García and José R. González, previously worked with Santander Bank which was responsible for issuing much of the island’s debt in the first place (Meléndez & Martínez, 2017). The Puerto Rican public continues protests against severe austerity measures imposed by the FOMB, including severe cuts to public education, the closing of several hundred schools, rising costs of tuition for University, and cuts to healthcare support and food stamps and other public services (Mazzei, 2018).

PROMESA and the FOMB exemplify the complex relationship between the United States and the territory and the ongoing issue of the island’s status, which has been a divisive political issue for decades. On the one hand, the independent movement has sought support from the international community. Recently, the United Nations Special Committee on Decolonization has approved a draft resolution calling upon the United States to facilitate the realization of the right of Puerto Rican’s to self-determination (United Nations, 2018). On the other hand, a bipartisan group of lawmakers has recently introduced legislation to admit Puerto Rico into the Union as a 51st state (Montoya-Galvez & Begnaud, 2019). The unresolved status issue is a major barrier to developing a stable, equitable, and sustainable economic development model for the island, and has complicated the post-disaster response and recovery process.

Unique Transportation Challenges in Puerto Rico

Recovery efforts in Puerto Rico are also made more logistically difficult given that this is an island community. Goods cannot as easily be trucked in like on the mainland, and instead must arrive by boat or airplane. Transportation infrastructure and systems in Puerto Rico were severely tested by Hurricane María. The storm revealed deficiencies and vulnerabilities that must be planned for as the climate continues to change. For example, the Luis Muñoz Marín International Airport, was completely shut down for several days after the hurricane. The storm shut down power and damaged the radar system, navigational aids, communications infrastructure, and fuel systems. These damages complicated resources getting to the island (Lazo, 2017). The airport, normally the busiest in the Caribbean, stranded hundreds of passengers for several days. It began resuming full operations on October 4th (Aon, 2018).

While ports reopened relatively quickly after the hurricane, shipping containers languished for days and possibly weeks due to broken distribution chains, damaged stores, lack of fuel, and damage to the trucking infrastructure (Hernandez & Mufson, 2017). Roadways and bridges were severely damaged throughout the island, with initial estimates at \$240 million (Aon, 2018). PRHTA later identified nearly \$652 million in damages (PRHTA, 2018).

Prior to Hurricane María, Puerto Rico already ranked as having some of the worst transportation infrastructure and congestion problems in the nation. Since 2008, the Highway Performance Monitoring System of the Federal Highway Administration has ranked Puerto Rico's roads as some of the most deteriorated in the United States. Among states and territories, the island is ranked 51st in the road roughness index which is an indicator of road network conditions (Cortes-Chico, 2016). The island has 16,691 miles of roadways and 2,220 bridges of which half are structurally or functionally deficient (PR-DTOP, 2013). Fiscal deficit has prevented the government from keeping up with maintenance costs of infrastructure. The government is turning to privatizing highway segments as an alternative to meet the ballooning infrastructure, operations, and maintenance costs.

Overall, Puerto Rico is a heavily car dependent society with an extensive and crumbling road network and terrible congestion. The island has one of the highest rates of car ownership in the world, ranking among the top five nations for numbers of cars per 1000 people (World Atlas, 2019). The high rates of car ownership are largely due to government failure to invest in public transportation infrastructure, as well as rampant sprawl and uncoordinated land use. Efforts to build and expand alternative public transportation have been meager, sporadic, and marred by delays and budget overruns.

Puerto Rico's already crumbling transportation infrastructure has been significantly worsened by the impact of the 2017 hurricane season. From a transportation perspective, the experiences people went through during and in the aftermath of Hurricane María were no less than traumatic. Entire communities were isolated from aid due to roads that had been washed out by landslides or blocked by debris. As a result, people turned to impure water sources from nearby springs, and managed to stave off hunger through rationing and foraging for food. As mentioned previously, contaminated water resulted in an outbreak of leptospirosis, which killed at least 26 people (Sutter, 2018).

The public health and humanitarian crisis that many communities faced was in large part due to their isolation and lack of mobility. Gas shortages on the island in the aftermath of the hurricane María forced people to wait in extremely long lines (some over 8 hours) to try to fill their tanks. In addition, thousands of people lost their vehicles due to flooding and were forced into deeper financial troubles to

meet their mobility needs. One in every five Puerto Rican's reported damage to their vehicles during the storm (Hernandez, 2018). In the weeks following the hurricanes, heavy rains caused a series of flash floods that nearly killed people stuck in their cars on the streets in floodplains (Mendez, 2017).

In the past year since the passage of Hurricane María, transportation infrastructure has become the top issue for Puerto Ricans. According to a new Washington Post-Kaiser Family Foundation survey, when asked where "more resources are necessary," 93 percent of Puerto Ricans now say "repairing roads and highways," (Hernandez, 2018). Transportation infrastructure is at the top of the list, outranking other options like helping people find jobs, repairing damaged homes and schools, and repairing the electrical grid. Increasingly, people are struggling to meet the rising costs of maintaining personal auto-mobiles on the pot-marked roads. Unrepaired routes have paralyzed economic activity in central municipalities like Utuado and Jayuya. The public is skeptical that the government will deliver on its promise to repair roads, given many unmet promises in the past. The government has failed to invest in durable and quality concrete and materials. Residents have taken to filling in the potholes with their own homemade concrete formulas (Hernandez, 2018).

This study is of timely relevance, as the Government of Puerto Rico has published a rapid succession of Action Plans that will govern the \$19.9 billion federal allocation to disaster recovery on the island (Puerto Rico Government, 2018). In addition, this study may inform several transportation planning documents that have either been released or are up for review. For example, the Puerto Rico Highways and Transportation Authority (PRHTA) has recently released its *Final Fiscal Plan for 2018-2023*. The Authority has identified more than \$700 million in damages from Hurricane Maria, and this plan would obligate \$138.8 million annually from the Federal Highway Administration, and \$20 million from the Federal Transit Administration (FTA) for recovery needs (PRHTA, 2018). Given the short time horizon of the plan, there is a danger that assets already vulnerable to the impacts of storm surge and SLR will simply be rebuilt. Given the scarcity of resources, there is a critical need to optimize expenditures on the transportation system to ensure the longevity of the assets. In addition to the PRHTA's plans, several transportation plans are up for review including the island-wide Long-Range Transportation Plan, and San Juan's Comprehensive Transportation Plan. The results of this paper may be useful to transportation planners responsible for revising these documents.

Relevant Plans and Studies:

There are several existing plans, drafts of plans, and RFPs that are relevant to the current study. A major issue in planning in general, and an issue that is particularly problematic in Puerto Rico, is the existence of a multitude of plans, but a lack of consistency, plan alignment, and plan implementation. There is an entire literature on plan quality evaluation and plan alignment that has emerged out of the hazard's literature (Alterman & Hill, 1978)|(Berke & French, 1994)|(C. Baer, 1997)|(Lyles & Stevens, 2014). While a review of this literature is beyond the scope of the current study, the concepts of aligning plans remains an integral and guiding principal.

This study has identified five plans that both inform and may be informed by the content of this paper. While these plans do not constitute a comprehensive review of all plans related to the study topic, they include some of the most relevant and influential documents based on their legal framework, jurisdiction, and implications for allocations of public dollars. These plans include:

- Municipality of San Juan: Comprehensive Transportation Plan (RFP currently published)
- Municipality of San Juan: Draft - Updated Multi-Risk Mitigation Plan (*Actualización del Plan de Mitigación Multi-Riesgo - Municipio Autónomo de San Juan – Borrador*) (2018)
- DTOP: Long Range Transportation Plan – (published in 2013)
- PRHTA: Final Fiscal Plan 2018-2023 (published in 2018)
- Government of Puerto Rico: Disaster Recovery Action Plan – Final Version Approved by HUD (published February 28, 2019)
- PR-DNER: Phase I: Sea Level Rise Adaptation – Review of Design Criteria for Coastal Infrastructure in Puerto Rico (published in 2015)

The following spreadsheet explores the degree to which these plans have incorporated considerations of equity and uncertainty relating to SLR and storm surge, as well as the transportation assets considered in the plans.

Figure 6: Comparison of Relevant Plans

Plan Details			Equity			Critical Infrastructure	Climate Change			
Plan	Entity / Jurisdiction	Date Published	Addresses equity explicitly in plan / RFP	Demographic / equity analysis and indicators used	Equity Analysis Included or Implied	Transportation assets analyzed	SLR risk explicitly addressed	Storm Surge risk explicitly addressed	Climate risk / uncertainty acknowledged	Climate Change Analysis Included or Implied
Puerto Rico - Disaster Recovery Action Plan: Amendment February 28, 2019 - Final version approved by HUD	Government of Puerto Rico	2019	Yes	Includes social vulnerability analysis with 27 social characteristics analyzed at the census tract level. Categories of characteristics analyzed include: *Age *Race *Housing types *Income *English proficiency *Education *Employment characteristics *Auto ownership *Poverty *Gender	Yes	*Bridges and culverts *roads *Sidewalks *Signage *Transit *Seaports *Airport	Yes - though does not use a specific range	Yes - notes storm surge measurements of 9 feet experienced during Hurricane María	Yes	Yes
Phase I: Sea Level Rise Adaptation – Review of Design Criteria for Coastal Infrastructure in Puerto Rico	PR - Department of Natural and Environmental Resources	2015	Yes	Includes reference to case studies that have considered vulnerable populations but does not include detailed analysis.	Yes	*Assesses critical infrastructure under the jurisdictions of PRDOT	Yes - adopts climate projections developed by the U.S. Army Corps of Engineers (USACE), which account for a 0.5- to 1.0 meter (1.6 - 3.2 foot) increase in SLR by 2100.	Yes - proposes design criteria accounting for a 100-year, 24-hour storm event "plus a 1-foot freeboard based on a storm surge and a high tide with a return period of 10 years taking into consideration SLR"	Yes	Yes
Draft - Updated Multi-Risk Mitigation Plan for the Municipality of San Juan (Actualización del Plan de Mitigación Multi-Riesgo - Municipio Autónomo de San Juan - Borrador)	Municipality of San Juan	2018	Yes	2010 Census data used: *Population *Housing *Renters *Pop under poverty *High school education *Vehicle ownership *Dependency on public assistance *Over 65 years old *Single parent household	Yes	Analyzes over 31 types of critical infrastructure, including roads, bridges, airports, and ports	Yes - detailed analysis of locally specific SLR trends, uncertainty, and risk: SLR trends show 3mm (0.11 inch) annual SLR in north coast, and 2mm (0.8 inch) in south coast. By 2100, estimates SLR in range of 40 - 345 centimeters (1.31 - 11 feet). Includes detailed erosion analysis but maps not yet published.	Yes - detailed analysis of flood, hurricane, and storm risk.	Yes	Yes

Plan Details			Equity			Critical Infrastructure	Climate Change			
Plan	Entity / Jurisdiction	Date Published	Addresses equity explicitly in plan / RFP	Demographic / equity analysis and indicators used	Equity Analysis Included or Implied	Transportation assets analyzed	SLR risk explicitly addressed	Storm Surge risk explicitly addressed	Climate risk / uncertainty acknowledged	Climate Change Analysis Included or Implied
Puerto Rico Islandwide Long Range Transportation Plan - Final Report	DTOP- PR	2013	Yes	Includes public involvement plan and outreach plan. Includes analysis of 2010 Census for following indicators: *Ethnicity *Race *Income and Auto Ownership *Housing types and household size *Employment *Education Level *Language proficiency *Age (60 years +) *Disability	Yes	*Highway system *Public Transportation *Bicycle and Pedestrian facilities *Seaports *Airports *Freight	*Yes - Referred to and implied under Goal 4: 'Promote environmental sustainability'. Acknowledges SLR projections of 1 foot by 2040 and 2 feet by 2060. Acknowledges other planning initiatives focused on SLR at island-wide level.	*Yes - suggests improved coordination with FEMA and U.S. Army Corps of Engineers on hurricane scenario analysis, and to revisit storm-surge mapping as it relates to transportation risk and response.	Yes	Yes
PRHTA Final Fiscal Plan 2018 - 2023	PRHTA	2018	No	No	No	*Highways and roads *Bus system *Tren Urbano	No	Implied through analysis of damage from Hurricane María	No	No
Request for Proposal of Professional Services for the Development of a Comprehensive Transportation Plan for the Municipality of San Juan	Municipality of San Juan	Current	No	N/A	Implied - RFP requests public involvement program and analysis of demographic trends	Requests comprehensive analysis of transportation assets	No	No	No	Included - RFP requests analysis of 'environmental considerations'

As this table shows, many of the plans are actively incorporating considerations of equity as well as uncertainty related to climate change. The plans that are most specific about the range of SLR considered are the PR DNER 2015 study, and the Draft - Updated Multi-Risk Mitigation Plan for the Municipality of San Juan. These plans consider a SLR range of 1.6 – 3.2 feet and 1.31 – 11 feet respectively. While these plans are quite explicit in addressing SLR and storm surge, the transportation-oriented plans are less explicit. Of most pressing concern to this study is the PRHTA Final Fiscal Plan 2018-2023, which does not explicitly consider equity or uncertainty associated with SLR and storm surge. This is particularly concerning given that the purpose of this plan is to obligate “\$3.1 billion of capital expenditures from FY18 to FY23, including \$2.25 billion for highway-related CIP, \$652 million for Maria-related emergency repair, and \$146 for HTA’s transit-related CIP” (PRHTA, 2018).

The content, focus, and limited time-horizon considered in this plan is a major concern for the current study. First, the content does not include considerations of equity, but instead justifies expenditures based on a rhetoric of ‘efficiency’ and ‘economic development.’ Second, the plan disproportionately obligates federal dollars to repairing a transportation system that has proven to fail in the past, and that may be vulnerable to future climate risks. Its limited time horizon fails to evaluate the future risks that the impacts of climate change might pose to short-term investments. Instead of building a more resilient and sustainable system, this plan feels more like a knee-jerk reaction to capture federal funds.

Finally, the plan appears to obligate a disproportionate amount of funding to rebuilding the highway system, seeking only a small fraction of the total for transit-related CIP. Focusing investment in the highway system contradicts some of the language in the Puerto Rico Long Range Transportation Plan, especially parts that highlight urban sprawl as a major land use and transportation issue in Puerto Rico. The LRTP explicitly addresses costs associated with sprawl, including over-reliance on the private automobile as a mode of transportation, and resulting issues like congestion. The plan calls for a more consolidated land use strategy.

At the same time, the language in the PRHTA plan may be a reflection of the difficult political position that the Puerto Rico government is in with relation to the federal government. Given its territorial status and current debt crisis, the Puerto Rican government must currently defend its ability to properly manage public funds. The short planning time-horizon is also a function of the way that federal funds are allocated and may reflect larger systemic problems and constraints in how federal dollars are spent. It is possible that federal constraints inhibit the ability of local agencies to appropriately coordinate between their plans. Strict federal deadlines and entities like PROMESA and FOMB may inhibit or disrupt local efforts at plan coordination.

3. Desktop Analysis: Scope, Methods, and Data Sources:

a. Project Study Scope:

Geographic Scope: The geographic scope is the San Juan Metropolitan Area, consisting of the municipalities of San Juan, Bayamón, Carolina, Cataño, Guaynabo, and Trujillo Alto.

Time horizon: This study considers a time horizon of 2050 and 2100.

Climate stressors: The climate stressors considered in this study is Sea Level Rise and Storm Surge. Specifically, SLR scenarios of 2ft, 4ft, 6ft, and 9ft are considered, where the 6ft and 9ft scenarios consider risk associated with unknowns in the climate system, as well as serving as proxies for storm surge events. A major limitation of this study is that it considers only the bathtub model and does not include a more sophisticated model for storm surge, such as taking into account effects from wave action.

Asset types: The asset types considered in this study are existing assets, specifically: 1) Roads, 2) Airports, 4) Ports, and 5) Public transit (Tren Urbano rail routes, AMA bus routes, público routes).

Demographic Indicators: Demographic indicators included in the study are those identified by the EPA EJSCREEN, as well as additional indicators gleaned from the literature review on equity.

b. Methods and Data Sources:

This study applies different methods gleaned from the background and literature review in order to assess Objectives 2 and 3 of the study, which involve the desktop analysis. This section discusses the methods and data sources for each objective in more detail:

Objective 2 is to conduct a basic, desktop analysis to examine the exposure of the road network and critical public transportation assets in the San Juan Metropolitan Area (SJMTA) to varying levels of SLR and storm surge scenarios possible in the 21st century.

To meet this objective, the study uses GIS to conduct intersection analysis to isolate and measure the length of segments of the transportation networks that will be impacted under different scenarios of SLR and storm surge. The results section displays the findings in maps and quantifies the number of miles of the transportation asset exposed under different scenarios.

Transportation Assets:

The study obtained data on transportation assets from the following sources:

Transportation Asset	Source
Road Network	Humanitarian Open Street Map Team (HOTSOM, 2019)
Public Transit (Tren Urbano, AMA bus routes, Público)	Puerto Rico Government Open Data Portal, 2019
Ports and Airports	No public shapefiles found. Polygons for these shapefiles were digitally produced by the author in GIS.

SLR and Storm Surge

To estimate SLR and storm surge, the study uses elevation data from the National Oceanic and Atmospheric Association (NOAA), based on the latest 2018 LIDAR. LIDAR is short for “light detection and ranging,” and is a remote sensing technology that uses a pulsed laser to measure distance to the earth. Usually an airplane flies over a surface and shoots LIDAR to obtain a very precise three-dimensional model of the shape of the Earth’s surfaces (NOAA, 2019b). Specifically, this study uses results from the USACE FEMA Topobathy Lidar Digital Elevation Model (DEM) for the Main Island, Culebra, and Vieques, Puerto Rico (NOAA, 2018). These datasets are also available through NOAA’s Sea Level Rise viewer, a very useful tool for quickly assessing exposure to SLR (NOAA, 2019a). NOAA pre-processed the LIDAR results into imagery and elevation raster datasets, as well as SLR shapefiles that show areas that would be inundated under different scenarios, from 1ft to 10 ft.

Figure 7: Shooting Lidar



Source: (Dewberry, 2014)

This study chose to examine assets inundated under the 2ft, 4ft, 6ft, and 9ft SLR scenarios. The 2ft and 4ft scenarios were chosen because they are considered possible in the Caribbean region by the end of the century under low and intermediate emissions scenarios. The 6ft and 9ft SLR scenarios were chosen as they are considered possible under extreme emissions scenarios, and they also serve as a proxy for storm surge that is possible today. As demonstrated in the literature review, parts of the island experienced 9ft storm surge during hurricane Maria. Future studies may consider extending the ranges storm surge possible, as the Updated Multi-Risk Mitigation Plan for San Juan predicts that up to 18 feet of storm surge is possible in a Category 5 hurricane (MSJ, 2018). A major limitation of this study is the inability to take into account effects of wind and wave action.

Objective 2 is to incorporate an equity perspective into the desktop analysis by also examining the sociodemographic characteristics of communities exposed to SLR and storm surge, with a focus on themes of social vulnerability, environmental justice, and transportation disadvantaged communities.

To meet this objective, the study examines indicators of social vulnerability and transportation disadvantaged communities. It uses GIS to examine the spatial distribution of these populations, their exposure to SLR and storm surge scenarios, and their relationship to transportation assets. Based on the literature review, the study attempts to enhance EPA’s EJSCREEN to be more locally and contextually specific.

EJSCREEN Data:

As discussed in the literature review, the EJSCREEN currently has two major demographic indexes and 11 different environmental indexes. The demographic indexes allow the user to quickly screen for populations that might be more vulnerable or susceptible to environmental justice issues. The first index includes just two populations, low-income and minority. The second index is a bit more robust in that it includes an additional four factors: less than high school education, linguistic isolation, individuals under age 5, and individuals over age 64. EJSCREEN data for Puerto Rico from 2018 were downloaded from EPA’s website for the purposes of this study (EPA, 2018).

Additional Demographic Data:

The 6-indicator demographic index may need to be adjusted to better distinguish vulnerable populations in Puerto Rico. Specifically, the definitions associated with indicators 2 (minority) and 4 (linguistic isolation) may not be as useful in the context of Puerto Rico. Regarding the minority definition, most everyone might be considered a non-white minority because of their latino heritage. Regarding linguistic isolation, people who do not speak English may not experience linguistic isolation because the dominant language in Puerto Rico is Spanish. Given these potential caveats, it is necessary to first map and examine these indicators in Puerto Rico to test their relevance, and also consider other indicators that may be more appropriate. Perhaps other racial characteristics like 'Blacks' may be a better indicator for the 'minority' category. Also, given the findings from the hazard's literature, it may be interesting to examine the exposure of women to SLR and storm surge.

In addition to these demographic indicators, given that a larger purpose of this research is to inform transportation planning, this study examines characteristics of transportation disadvantaged or transit-dependent populations. Specifically, the study includes populations with no-vehicles available and with long-commutes to work (>30 minutes). This study obtained all of these additional demographic indicators through the U.S. Census American Community Survey, 2017 5-year estimates.

c. Audience for study

The audience for this paper is federal and state agencies and municipal offices who are involved in hurricane recovery and long-range transportation and land use planning in the San Juan Metropolitan Region. Currently, agencies are making critical decisions about how to invest federal allocations for hurricane recovery. When planning how to invest these allocations in the short term, agencies should consider risks and vulnerabilities posed by climate threats in the future, so as not to rebuild systems that are bound to fail. The following entities have been identified as potential audiences for this research paper:

Federal Agencies:

- Agencies responsible for administering federal aid and recovery packages, such as FEMA and HUD
- Agencies involved in transportation planning, such as FHWA and FTA

Commonwealth Agencies:

- Puerto Rico Department of Transportation and Public Works (DTOP)
- Puerto Rico Highway and Transportation Authority (PRHTA)
- Puerto Rico Ports Authority (PRPA)
- Puerto Rico Planning Board (PRPB)
- Puerto Rico Department of Natural and Environmental Resources (DNER)
- Puerto Rico Department of Housing (PRDOH)

Municipality:

- Municipality of San Juan (MSJ): Planning and Territorial Organization Office
- Planning offices in the Municipalities of Bayamón, Cataño, Carolina, Guyanabo and Trujillo Alto

4. Results

The following section presents the results of the desktop analysis, which examines 1) the degree of exposure of transportation assets under varying scenarios of SLR and storm surge, and 2) characteristics of communities that are also exposed to SLR and storm surge, with a focus on socially vulnerable and transportation disadvantaged communities.

a. General Exposure in the San Juan Metropolitan Area

The map below illustrates the areas of highest exposure in the San Juan Metropolitan Area, as well as the transportation assets that are at risk. General areas facing more immediate exposure (2ft, to 4ft SLR) include:

1. Around the southern portion of the San Juan peninsula near the cruise ports
2. The northern portion of the Municipalities of Cataño and Guaynabo
3. Areas around the Caño Martín Peña Channel
4. The eastern portion of Santurce
5. Areas bordering the Laguna San José
6. The eastern portion of the Luis Muñoz Marín International Airport.
7. Northern Carolina

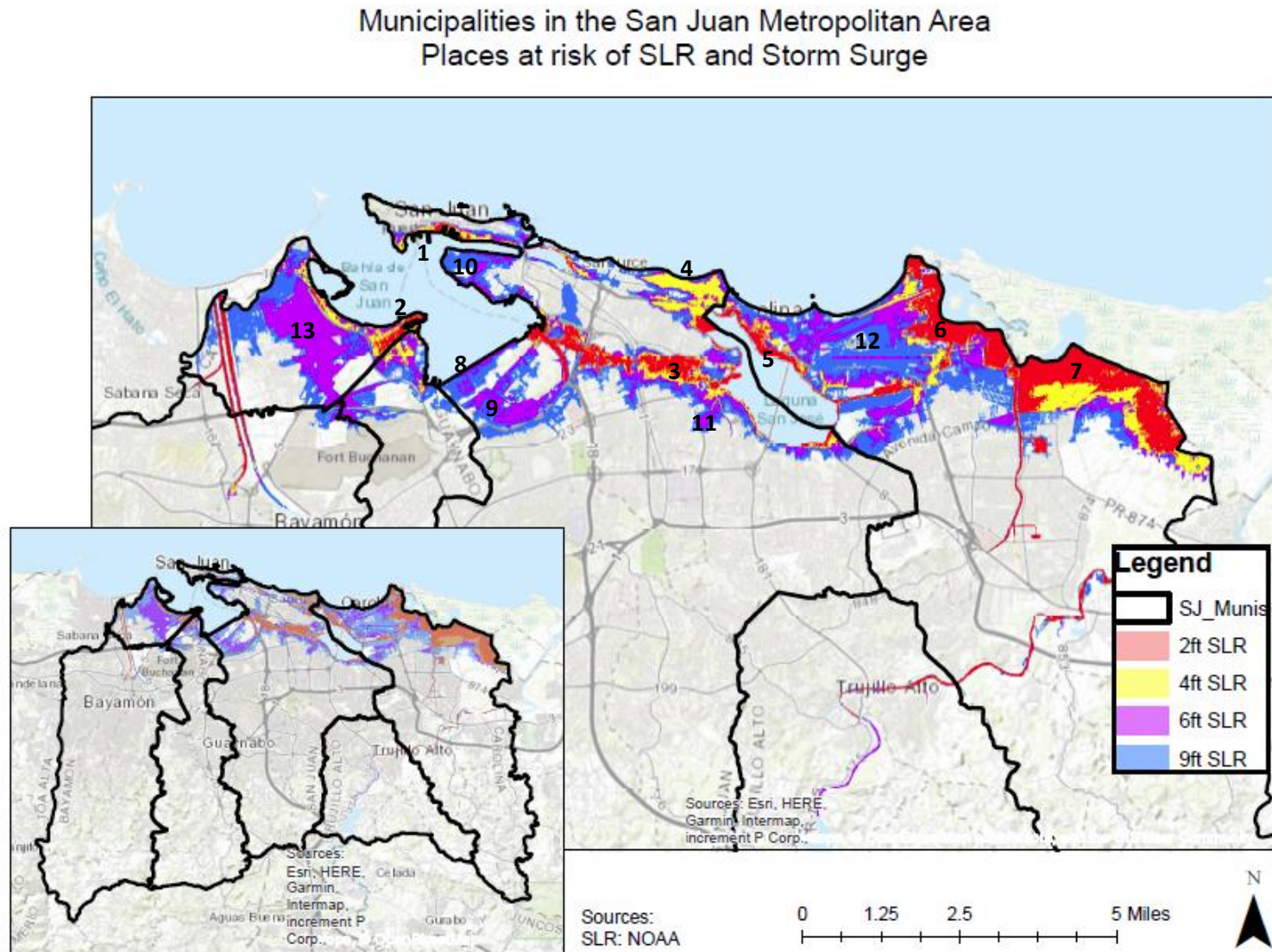
General areas that face risk to inundation at 6ft and 9ft SLR scenarios, or storm surge include:

8. The cargo port Puerto Nuevo
9. Inland along the John F. Kennedy expressway and the José de Diego Highway
10. The Fernando Ribas Dominicci Airport
11. Areas more inland around the Martín Peña Channel
12. The entire area of the Luis Muñoz Marín Airport in the Municipality of Carolina
13. Northern Bayamón

Figure 8 below serves as a reference map illustrating where these areas of risk are located by reference number.

Figure 9 then serves as a reference map to understand the general layout of the transportation assets and transit routes in the San Juan Metropolitan Area. The figures following these reference maps explore each transportation asset at risk by asset type and quantify the number of miles of the asset exposed under different scenarios. The section after that examines the demographic characteristics of the populations exposed. Demographic characteristics associated with environmental justice and transportation disadvantaged populations are examined.

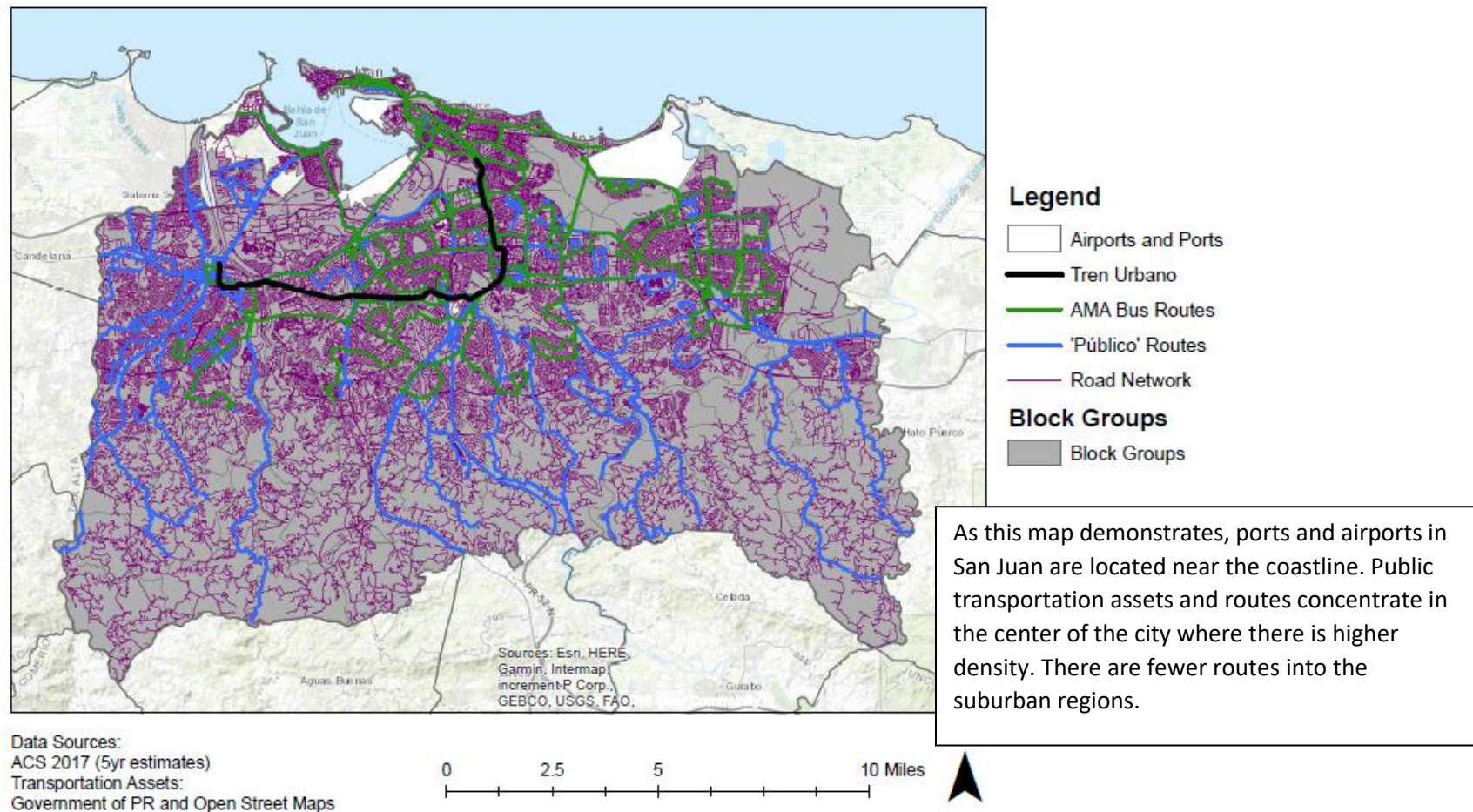
Figure 8: Places at risk of SLR and Storm Surge – Reference Map



b. Transportation Network in the San Juan Metropolitan Area

Figure 9: Reference Map - Transportation Assets and Transit Routes

Reference Map - Transportation Assets and Transit Routes in the San Juan Metropolitan Area



c. Exposure Analysis for Transportation Assets

Figure 10: Analysis of Road Network Exposed to SLR

Road Network Inundated at Different Levels of SLR

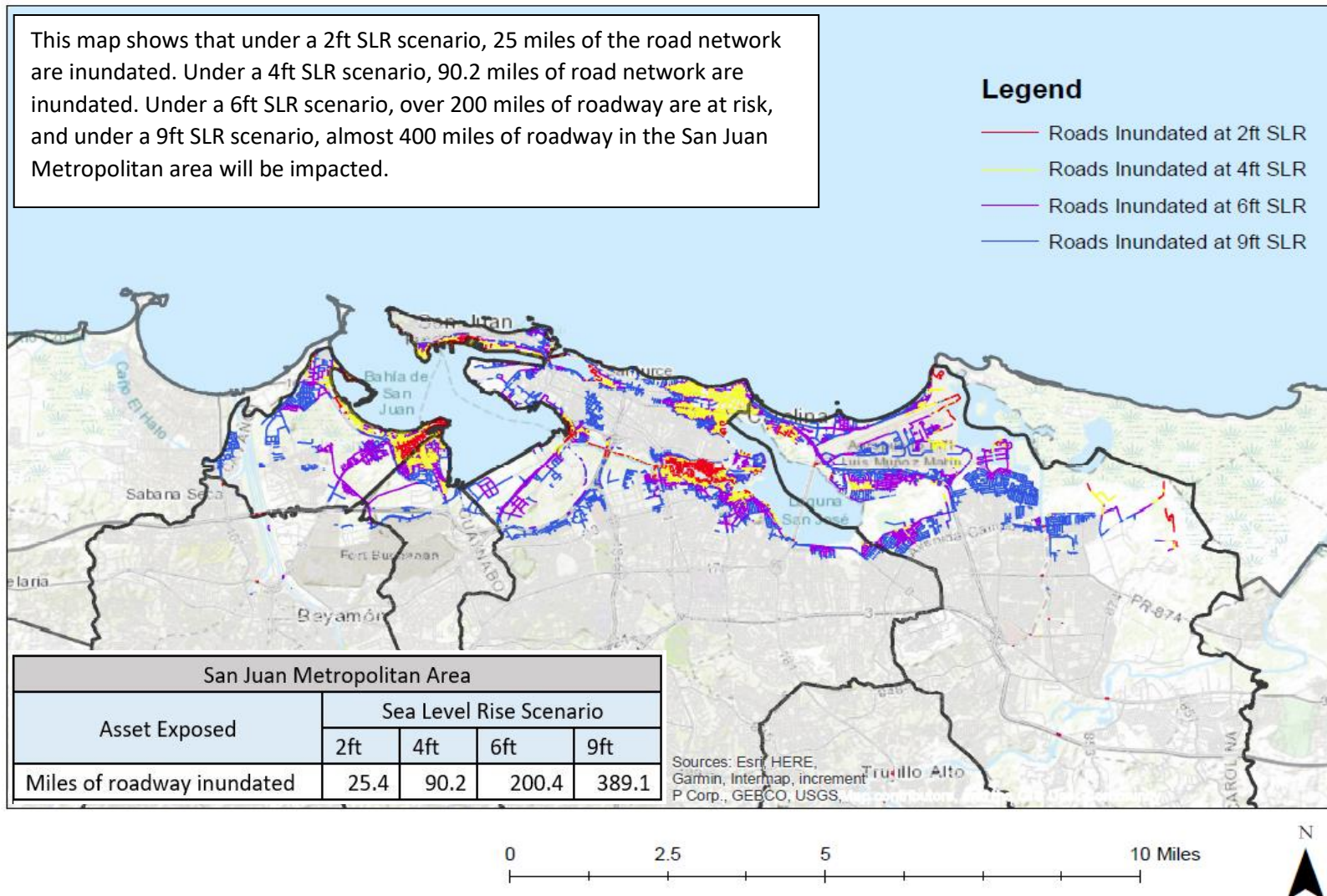


Figure 11: Analysis of Bus Network Exposed to SLR:

AMA Routes Alignment Impacted at Varying Levels of SLR

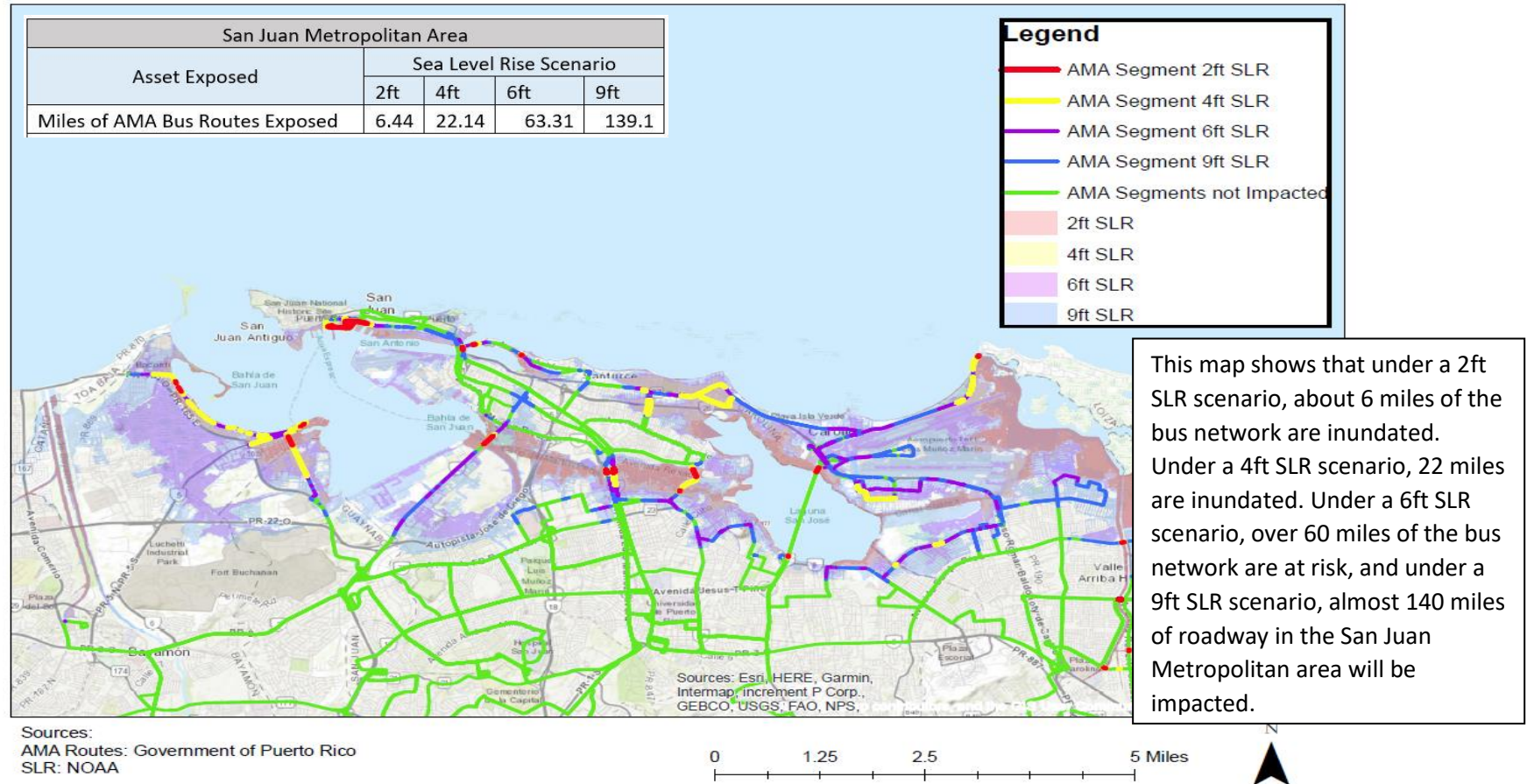


Figure 12: Analysis of 'Publico' Routes Exposed to SLR

Publico Route Segments Impacted at Varying Levels of SLR

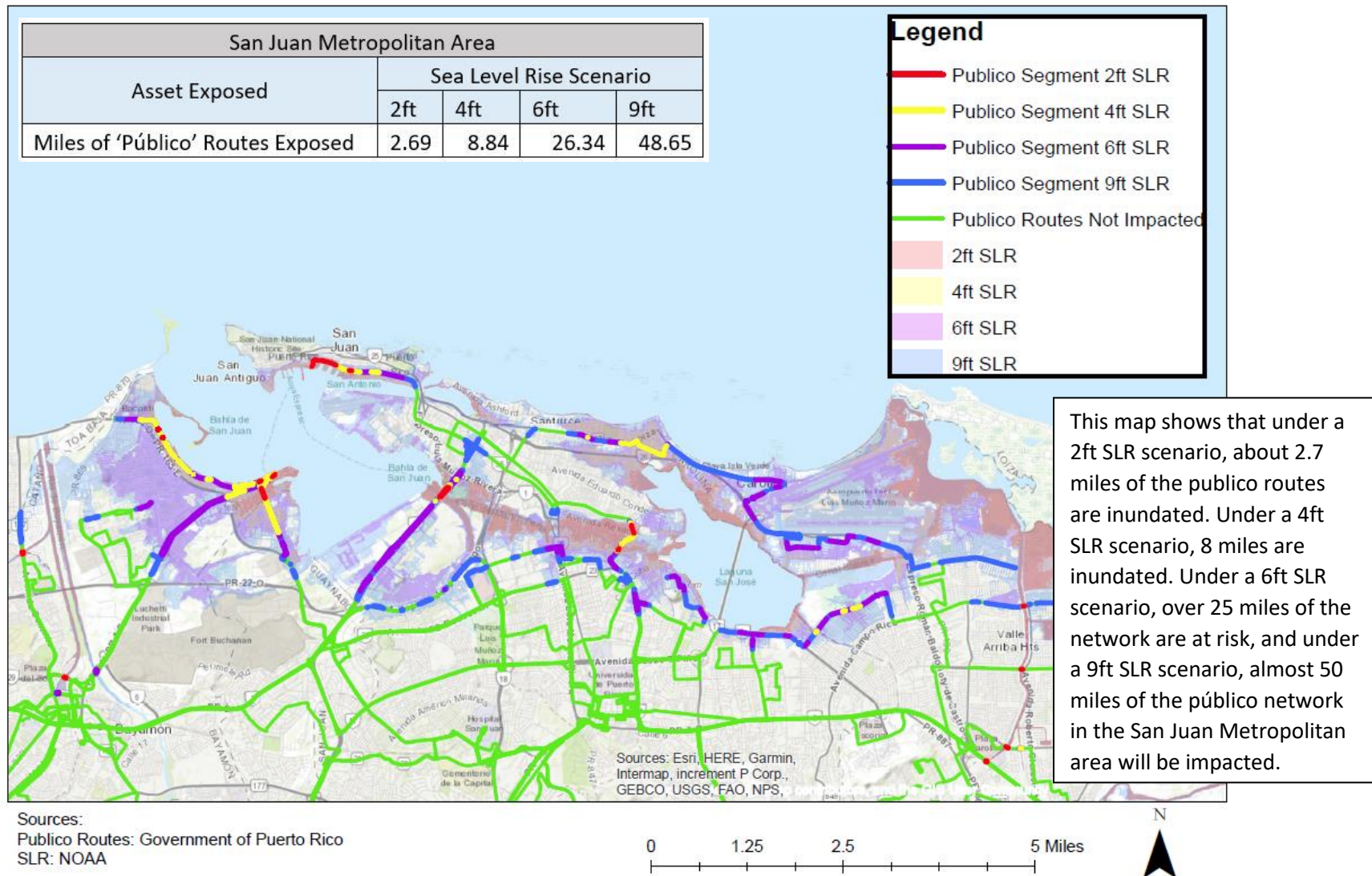


Figure 13: Analysis of Tren Urbano Alignment Exposed to SLR

Tren Urbano (Metro) Alignment Impacted at Varying Levels of SLR

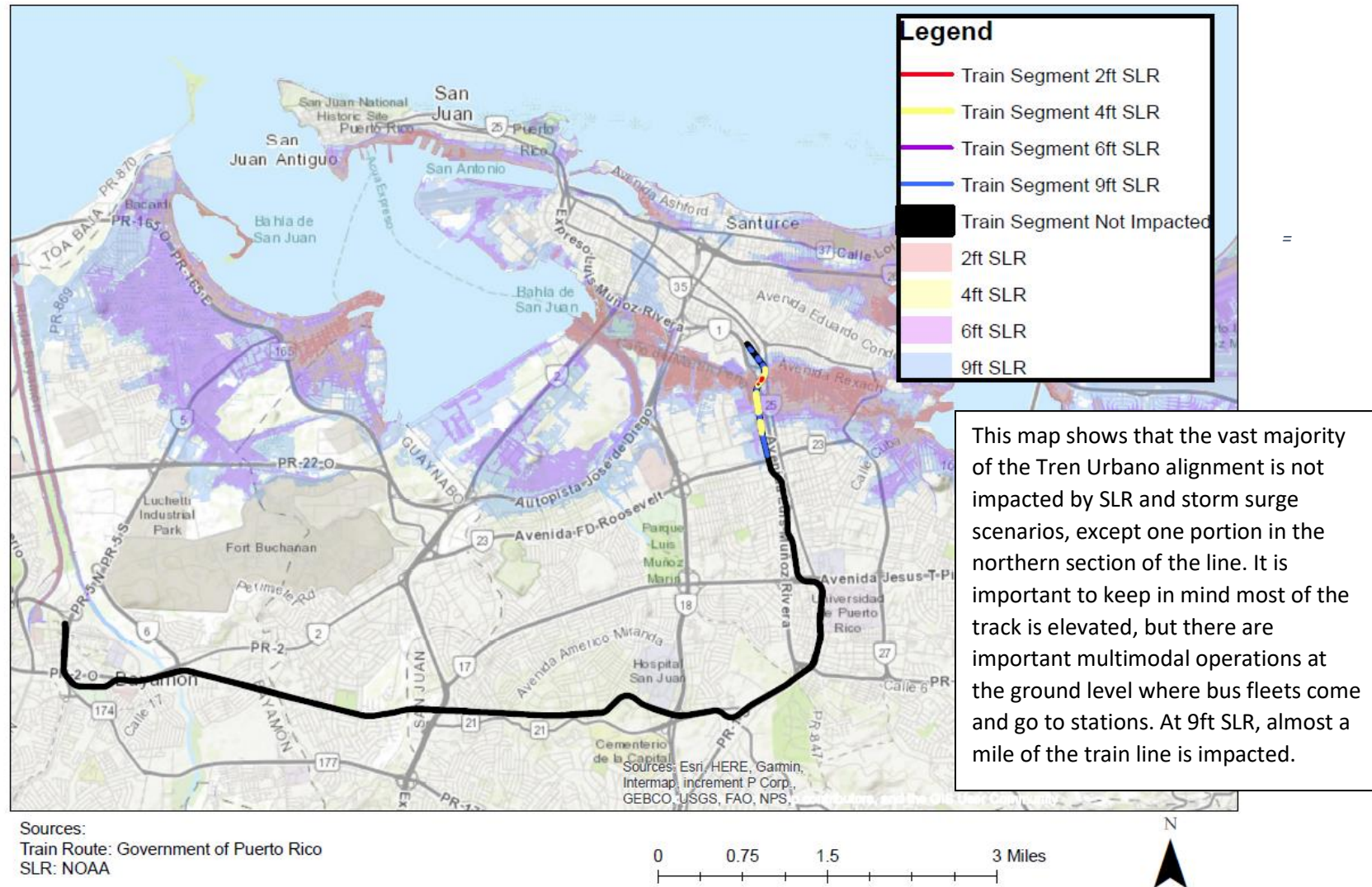
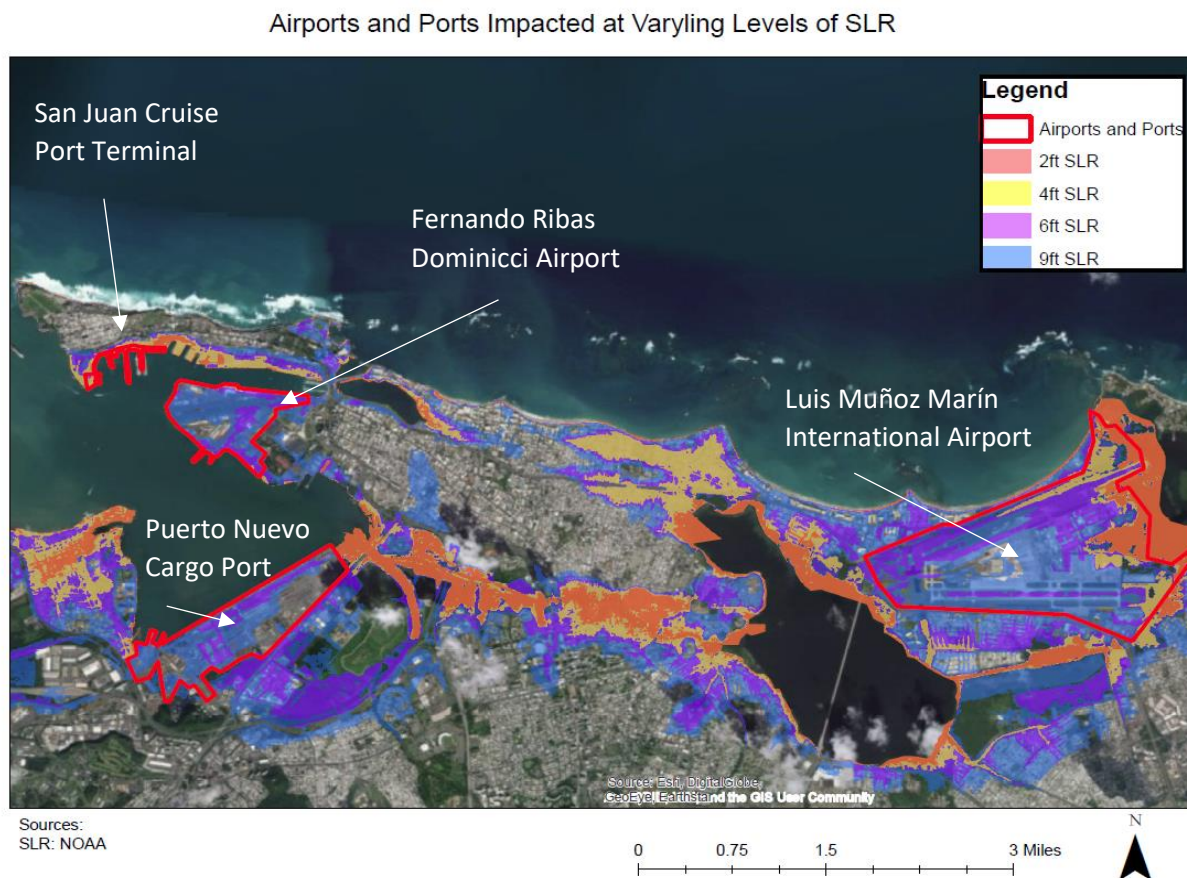
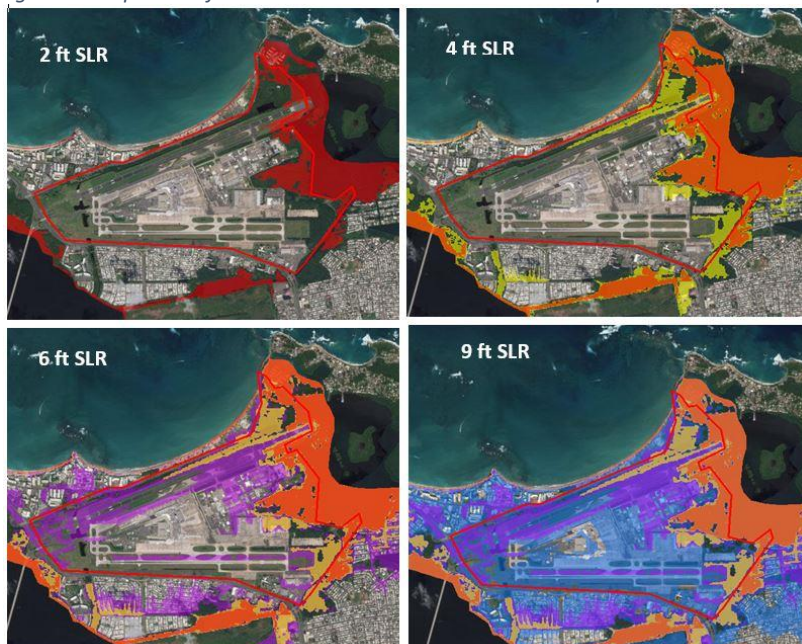


Figure 14: Exposure of major ports and airports to SLR



All the major ports and airports in the San Juan Metropolitan Area are at risk to SLR and storm surge. This is a major threat to the security and sustainability of the region, and poses a risk to all phases of

Figure 15: Exposure of the Luis Muñoz Marín International Airport



hazard mitigation, response, and recovery. Figure 14 on the left provides a closer look at the exposure of the Luis Muñoz Marín International Airport, which shows that even at a 2ft SLR scenario, portions of the eastern section of the airport are already exposed. Under a 4ft scenario, sections of the runways are at risk, and the runways are entirely inundated under a 6ft scenario. In the 9ft scenario, the airport is almost completely inundated.

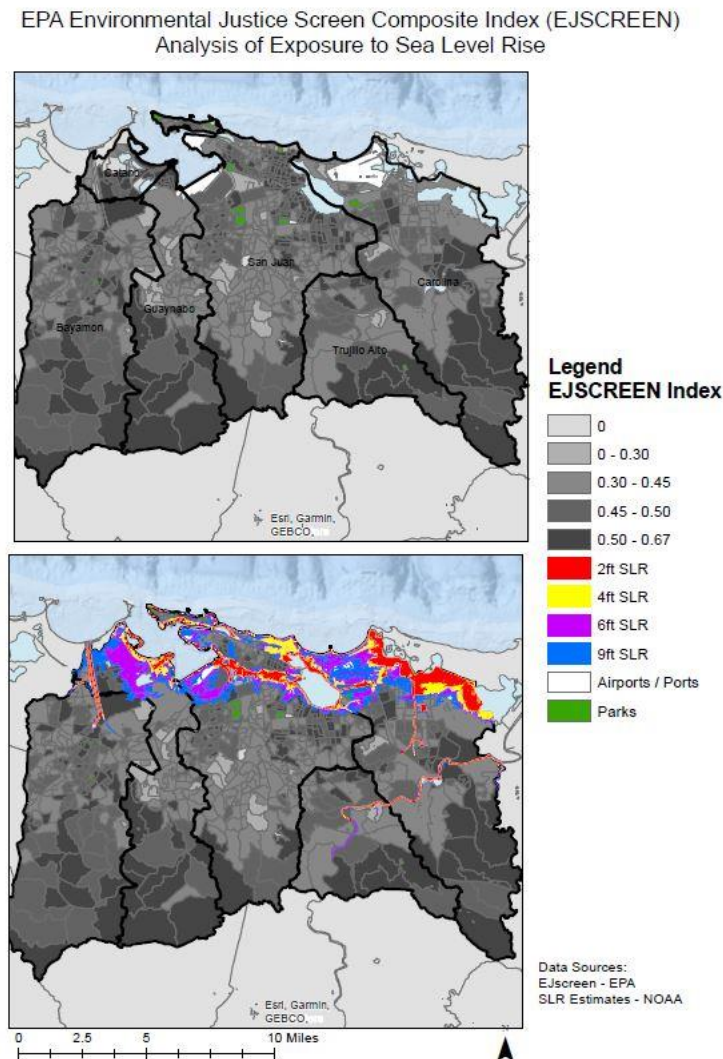
d. Analysis of EJSCREEN and Social Vulnerability

The following maps examine the demographic characteristics of the populations exposed to SLR and storm surge under different scenarios. First, the study examines the composite index and individual demographic indicators used in EPA's Environmental Justice Screening tool. Next, the study incorporates additional indicators of social vulnerability into the analysis, based on findings in the literature. To facilitate visual analysis, each indicator is displayed with and without the SLR and Storm Surge scenario overlays.

EJSCREEN Demographic Index and indicators:

Below is a map displaying the EJSCREEN demographic index based on the six indicators the EPA has chosen as its general screening tool for environmental justice issues.

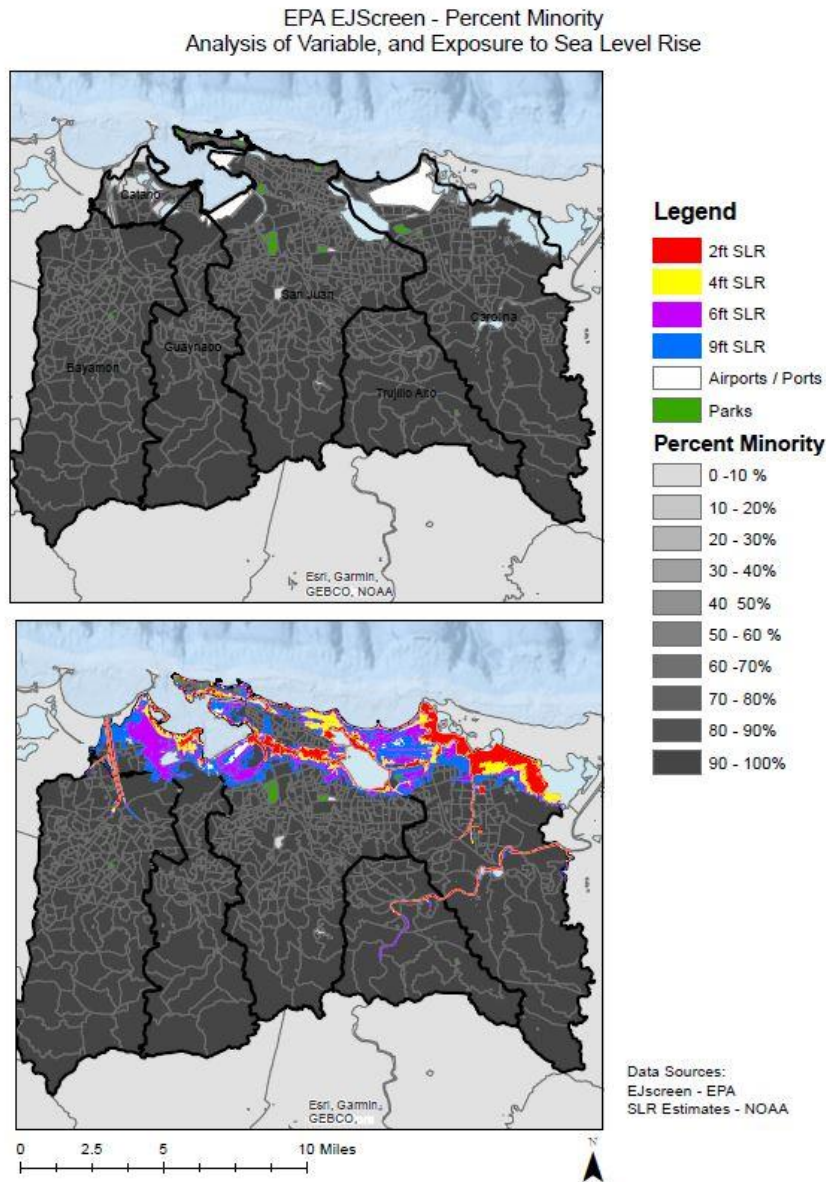
Figure 16: Composite EJSCREEN index



This map indicates that within the San Juan Metropolitan area, there are different pockets and regions of social vulnerability. A large portion of vulnerable populations are located in the southern suburbs, away from the threat of sea level rise and storm surge. Nevertheless, there are clusters of socially vulnerable populations at great risk, namely in the northern region of the Municipalities of Cataño by the Bay of San Juan, as well as along the Martin Peña Channel.

The following maps examine each indicator that forms the composite EJSCREEN index individually. Each indicator is analyzed in turn below in terms of the general spatial distribution of the population, vulnerability to SLR and storm surge scenarios, and relationship to public transportation assets.

Figure 17: Percent Minority



Percent Minority:

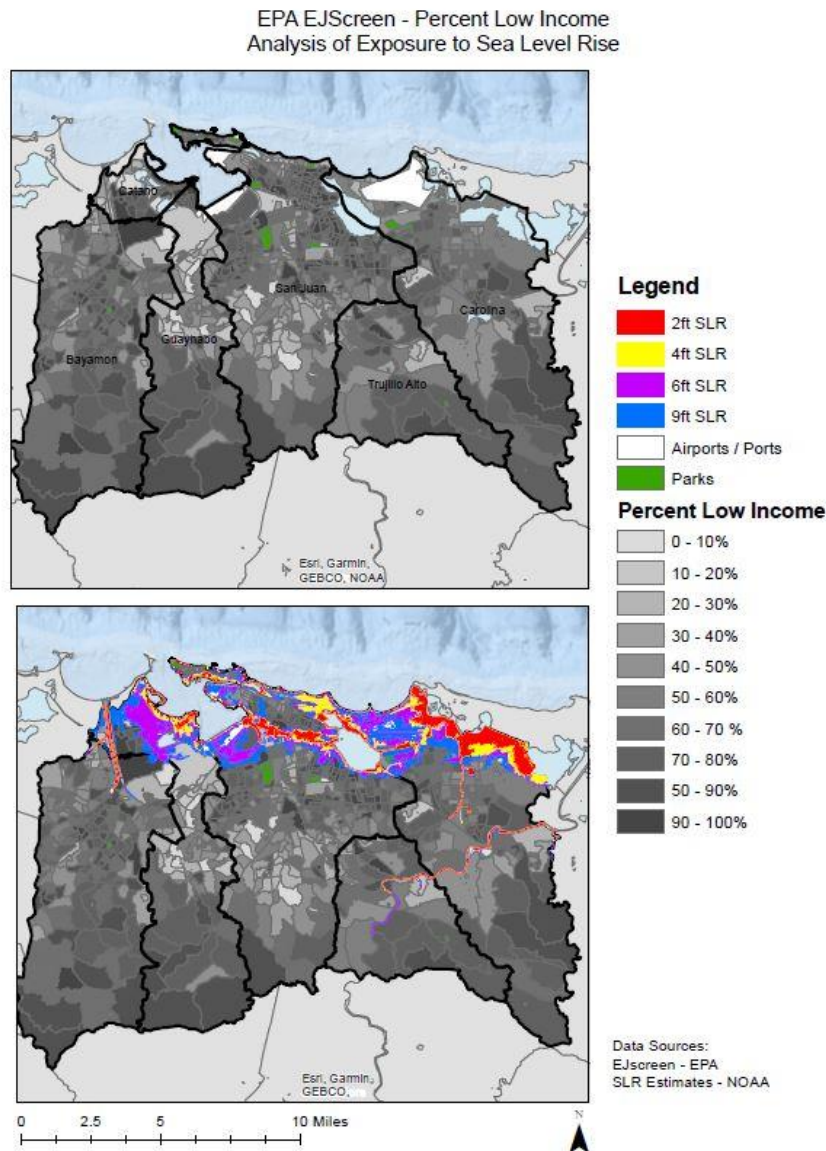
The first indicator in the EJSCREEN is percent minority, which the EPA defines as:

“The number or percent of individuals in a block group who list their racial status as a race other than white alone and/or list their ethnicity as Hispanic or Latino. That is, all people other than non-Hispanic white-alone individuals...” (U.S. EPA, 2016).

As shown in figure 17, almost the entire population of the San Juan Metropolitan Area is considered minority according to this definition, as it is likely that most people living in Puerto Rico identify as being of Hispanic origin. This distinction may be useful for comparing the population in Puerto Rico to the rest of the United States, but it does not allow for more fine-grain analysis of what might be locally considered as minority. As such, this paper will experiment with removing the minority indicator and incorporating other variables that are more locally specific.

Instead of using the EJSCREEN minority indicator, this paper suggests adding a variable to the EJSCREEN that examines the distribution of the Black population. Historically, there has been a significant amount of migration of Black populations from other places in the Caribbean. For example, the Barrio Obrero neighborhood around the Martin Peña Channel is largely composed of Black migrants from the Dominican Republic (Phippen, 2012). These populations have been historically marginalized and will be examined more closely in subsequent sections.

Figure 18: Percent Low-Income



Percent Low-Income:

Figure 18 displays the distribution of the low-income population in the San Juan Metropolitan Area. Low-income populations may be more vulnerable to SLR and storm surge, because they may not have the resources to evacuate or relocate out of harm's way. They also are likely to be less capable of affording a private automobile, and are therefore more likely to rely on public transportation for access to jobs, healthcare, and social services.

As shown by Figure 18, poverty is a major issue in the San Juan Metropolitan Area, a large proportion of the tracts having more than 50 percent low-income populations. Many low-income people are concentrated in the outskirts or suburbs of San Juan. While the suburban poor are not at risk of SLR, these communities do have minimal access to public transportation, with only a few público lines extending into these communities.

While a large portion of the low-income population resides on the outskirts of the city, there are also pockets of poverty throughout the city center and in coastal areas or along waterways that are susceptible to storm surge and SLR. Specifically, the community surrounding the Martín Peña channel has high rates of poverty, and these communities are currently at risk under the most immediate 2ft and 4ft SLR scenarios. These communities are better serviced by public transportation assets like the Tren Urbano (subway), bus, and público routes, but these routes in turn are at risk to SLR and storm surge as noted in prior analysis.

Poor communities on the shoreline of Cataño are similarly at immediate risk. Cataño is serviced by a ferry line that takes passengers directly across the bay to Old San Juan, but these ports may be at risk to SLR and storm surge as well, leaving these communities more vulnerable and isolated. Poor communities in Santurce behind Ocean Park are at more immediate risk, along with the road networks that provide bus services. Poor communities east of the airport and bordering Laguna San José are both immediately at risk to SLR and storm surge, and isolated from public transportation networks.

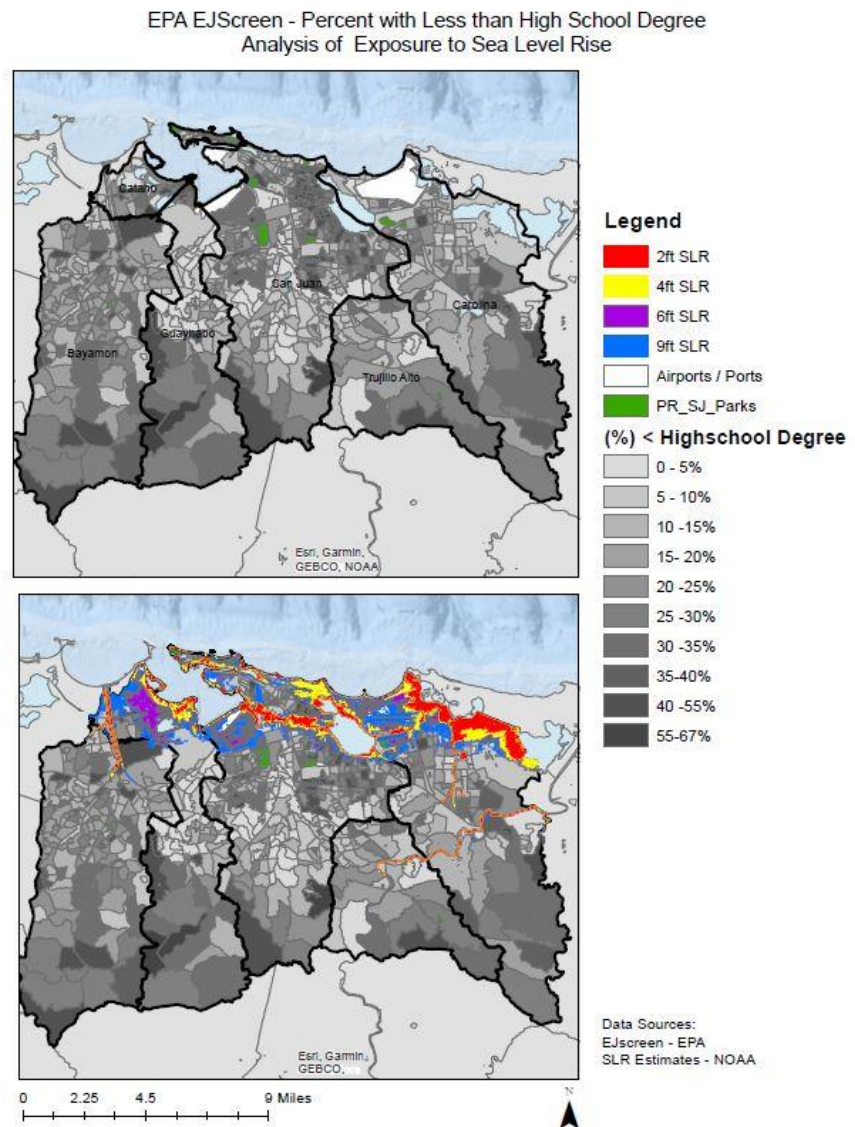
Finally, some communities in northern Bayamón, south of the airport, and in the wider area surrounding the Martín Peña Channel face risks associated with higher levels of storm surge and SLR, as indicated by the 6ft and 9ft scenarios.

Percent with Less than a High-School Education:

Figure 19 displays the distribution of populations with less than a high-school education. These populations may be more vulnerable to SLR and storm surge, because they may not be as aware of their risk or have access to the same education resources to understand their risk. In addition, their lack of education may reduce their ability to get jobs and have enough resources to relocate or evacuate out of harm's way.

Populations with less than a high-school degree are located in pockets of the suburbs of the Metropolitan Area, in the center of the city south of the Martín Peña Channel, bordering the Laguna

Figure 19: Percent with Less than High-School Degree



San José, and south of Puerto Nuevo. Those communities bordering the Laguna and near the Martín Peña Channel are most at risk to SLR and storm surge, while less educated populations south of Puerto Nuevo and in northern Bayamón are vulnerable to 6ft and 9ft SLR and storm surge scenarios. Populations located centrally seem to be relatively well served by public transportation assets like the Tren Urbano, público routes, and bus routes. However, the tract behind Puerto Nuevo is serviced by only one AMA route, and the tracts in the suburbs are more sparsely serviced by público routes.

Percent Linguistically Isolated:

Along with the ‘minority’ indicator, another variable that seemed like it might not be as appropriate initially within the context of Puerto Rico is the ‘Linguistic Isolation’ variable, which EPA defines as: “The number or percent of people in a block group living in linguistically isolated households. A household in which all members age 14 years and over speak a non-English language and also speak English less than “very well” (have difficulty with English) is linguistically isolated.”

This definition seems inappropriate in Puerto Rico, where the dominant language is Spanish. Lack of English fluency does not equate to linguistic isolation. Nevertheless, the ability to speak English very well does likely improve opportunities in the job market, and therefore may be more appropriately associated with educational and economic mobility. This is reflected when comparing maps from Figures 18, 19, and 20, where the spatial distribution of the ‘linguistically isolated’ seems to follow patterns of populations that are low income and have less than a high-school degree. Given these observations, this study will experiment with removing the ‘linguistically isolated’ variable from the final index.

Figure 20: Percent Linguistically Isolated

EPA EJScreen - Percent Linguistically Isolated
Analysis of Variable, and Exposure to Sea Level Rise

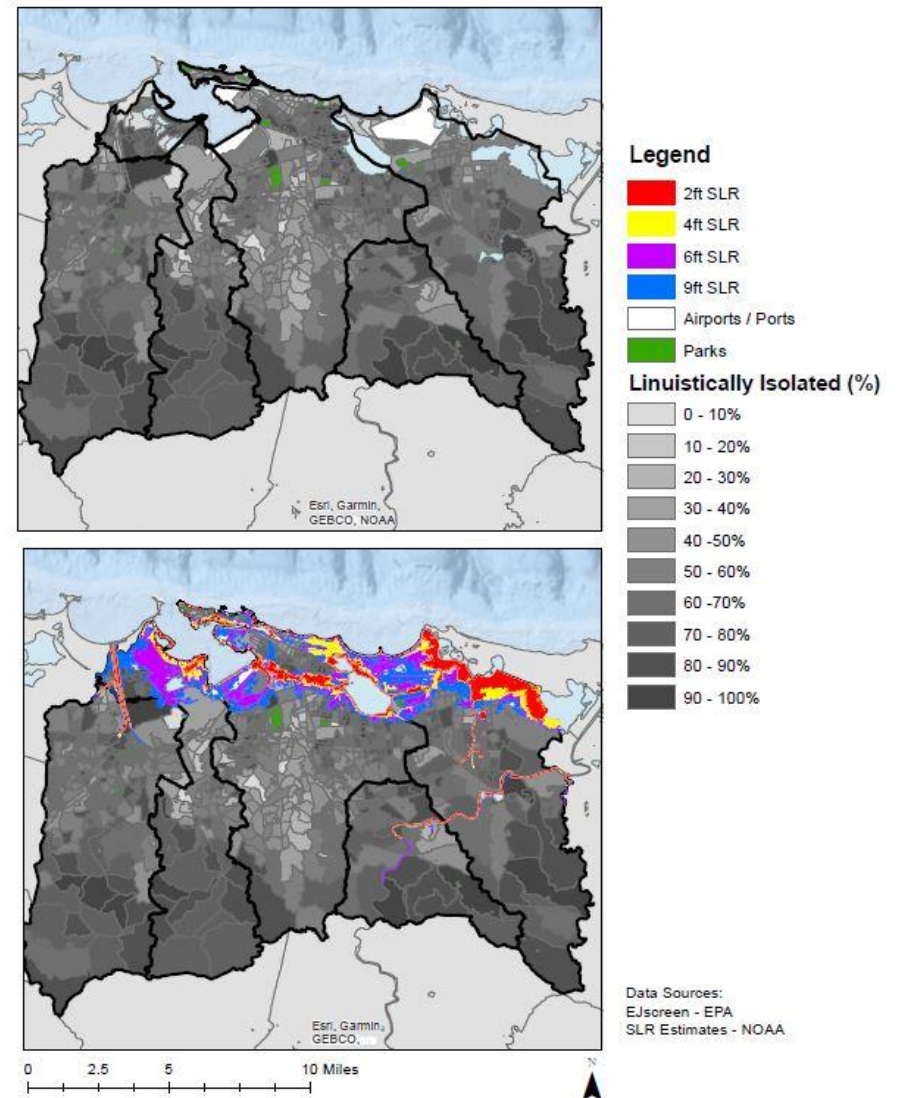


Figure 22: Percent Under Age 5

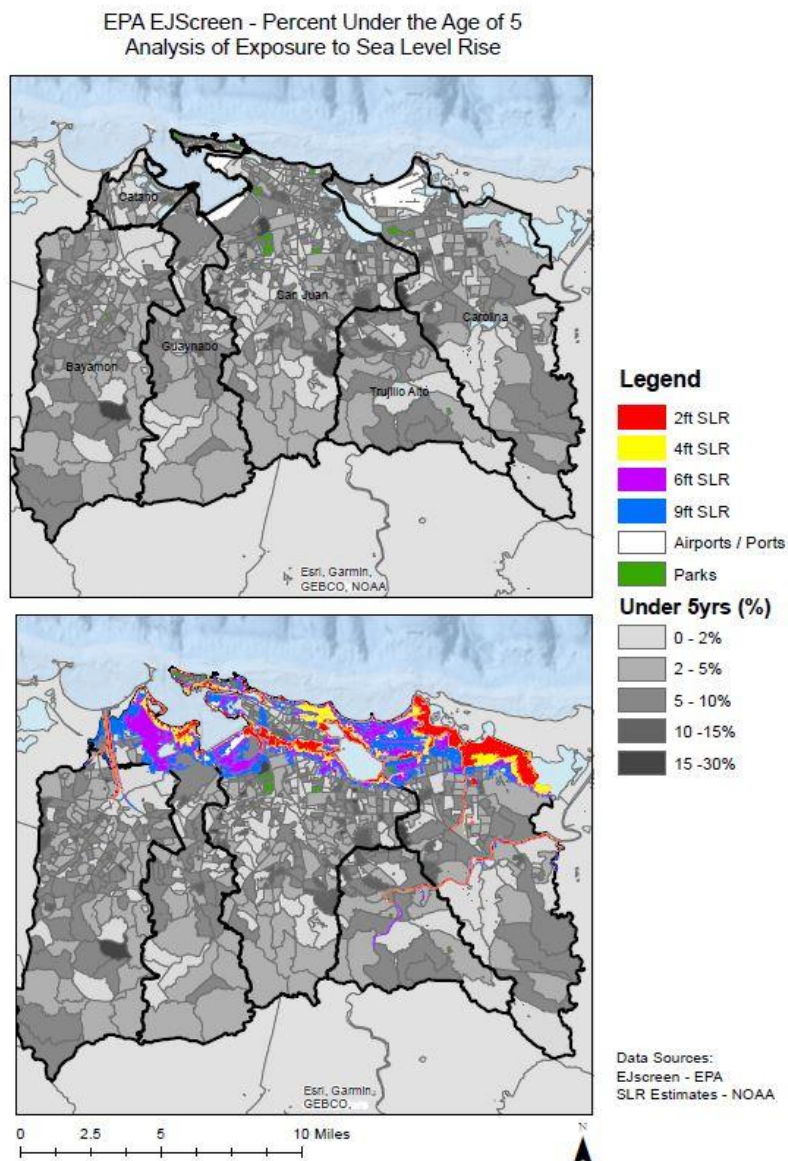
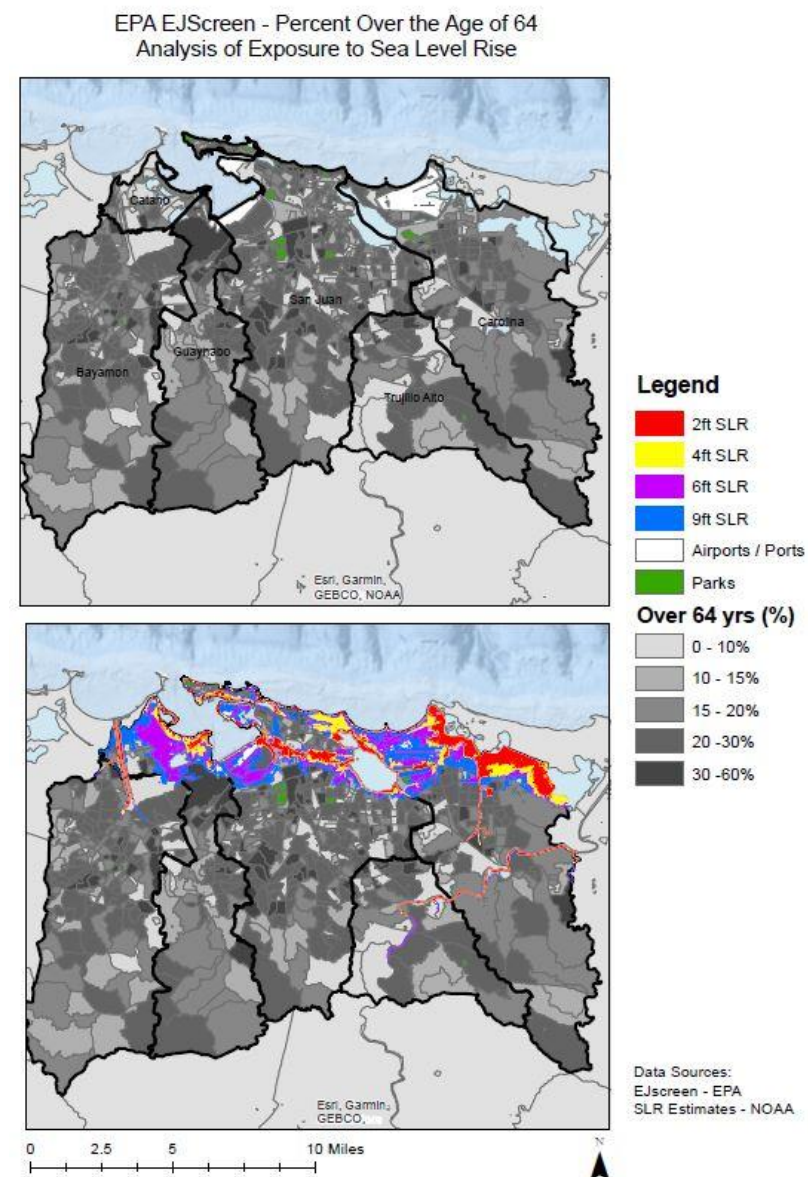


Figure 21: Percent Over Age 64



Percent Under the Age of 5

Young children under the age of 5 are more vulnerable to the impacts of SLR and Storm Surge as they are at a stage in their lives where they are heavily dependent on their parents. This population cannot easily adapt without the help of adults.

As shown by Figure 22, people under the age of five are generally evenly distributed throughout the metropolitan area. There are very few tracts where more than 15 percent of the population is under the age of five years old, though there are a few pockets as indicated by the darker tracts. One of these tracts is behind the Puerto Nuevo port, and is vulnerable to storm surge or SLR at 9ft.

Percent Over the Age of 64:

Like children under 5, people over age 64 are likewise typically less independent than other age groups, and therefore more vulnerable to SLR and storm surge. The elderly are often more prone to illness or disability, and have more difficulty moving around, evacuating, and relocating.

Figure 21 shows that there are a substantial number of tracts with high proportions of elderly (e.g.: between 30 and 60 percent). The elderly are somewhat randomly distributed, though there are clusters in the Condado neighborhood near the shoreline that might be more vulnerable to the impacts of SLR. However, as shown by figure 15, these populations are not low-income, and may represent well-off retirees with more resources. Housing structures in this part of Condado are also mostly high-rises, so people located on higher floors might not face immediate life-threatening risk from storm surge compared to populations in ground-floor households.

Additional Demographic Variables:

As mentioned previously, in addition to unpacking the EJSCREEN index, this study examines a few select additional demographic characteristics based on the hazard literature as well as the context in Puerto Rico. Two demographic variables are further examined: the Black population, and women. For this study, Blacks are considered an important minority community that might be overlooked by the EJSCREEN's minority variable. Women are another important subgroup that the literature has determined to be more vulnerable to the impacts of hazards (French et al., 2010). These two variables are examined further below to examine their spatial distribution, exposure to SLR and storm surge scenarios, and relationship to transportation assets.

Figure 23: Percent Black / African Origin

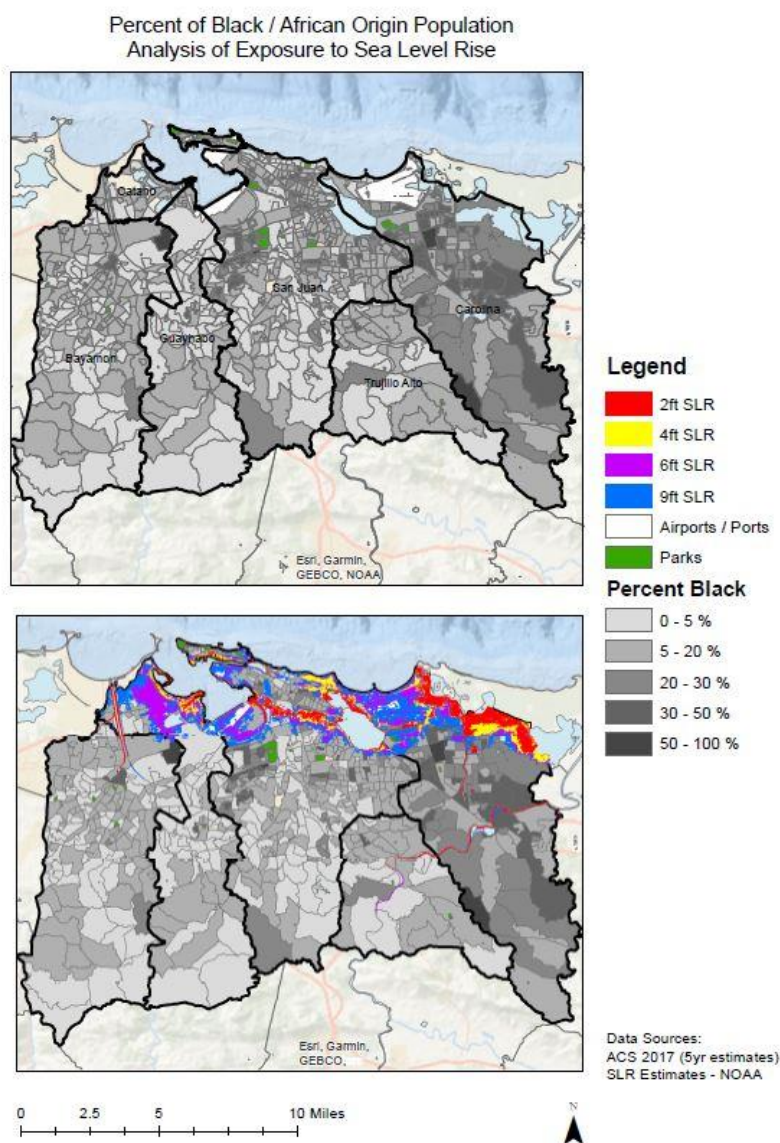
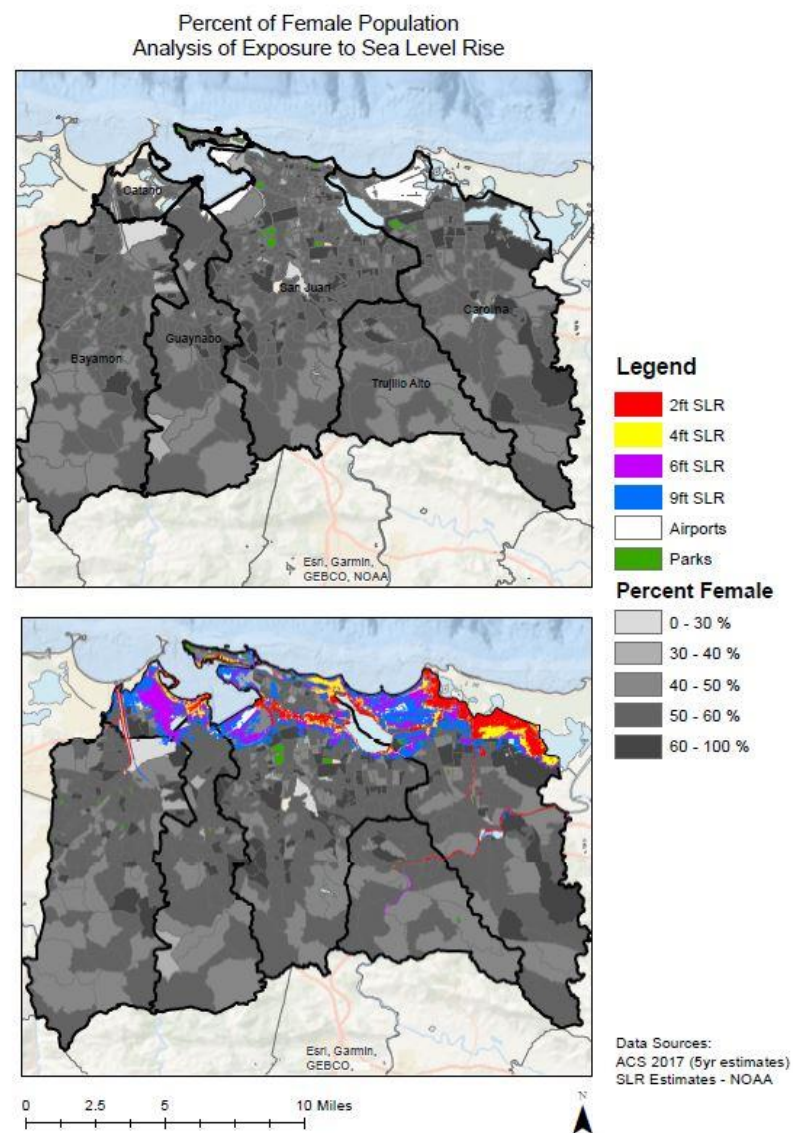


Figure 24: Percent Female



Percent Black / African Origin:

As discussed earlier, the EPA's definition of 'minority' for the EJSCREEN has limited utility in the context of Puerto Rico, where almost everyone is classified as being minority based on their Hispanic origin. In order to develop an indicator with more locally-specific relevance, this study examines the spatial distribution of the Black population in the San Juan Metropolitan Area, as this population has been historically marginalized (Fernández-Toledo et al., 2018).

Figure 23 shows that there are higher concentrations of the Black population on the eastern side of the city. Surprisingly, there do not appear to be high concentrations of people identifying as Black along the banks of the Martin Peña Channel as would be expected, given that this is a historically Black Dominican population. There are several possible explanations of this, such as demographic shifts or cultural interpretations of race. However, the most likely explanation is that this population is undercounted by the census, given its informal nature. According to the Urban Institute "Black communities across the United States have been undercounted for decades in decennial census" (Runes, 2019). Despite problems with possible undercounting, the variable does express a larger degree of variation than the EJSCREEN Minority indicator and is thus retained in the final index that is generated for comparison in this paper. A future area of research might be to develop a more robust definition and indicator of 'minority' populations based on local perceptions of what constitutes 'minority'.

Percent Women:

The literature pointed out that women are often an overlooked population in discussions of vulnerability to hazards (Peacock et al., 1997). In Puerto Rico, women are an especially important subgroup to consider given ingrained gender roles, a history of domestic violence, and burdens placed on female-headed households (Toro-Morn & Garcia-Zambrano, 2017).

With regards to the distribution of women, in Figure 24 the distribution appears mostly random and homogenous throughout the San Juan Metropolitan Area, with a majority of tracts having over 50 percent women. There are additional clusters and pockets where women constitute over 60 percent of the population, especially in the central and eastern portions of the metro area. Tracts that are majority women south of the Luis Muñoz Marín Airport are particularly vulnerable to SLR scenarios. Given that women have traditionally been overlooked in the hazard's reduction literature, this paper has retained this variable in the final composite index.

Transportation Disadvantaged Communities - Maps:

In addition to exploring the socio-economic variables included in the EJSCREEN, as well as additional variables that are important to the context of Puerto Rico and the hazards literature, this study also explores variables associated with transportation disadvantaged or dependent communities. Based on findings from the literature review, this study analyses two variables associated with transportation disadvantaged communities: households with no vehicle ownership, and households with long commutes (>30 minutes) to work. The distribution of these populations in the San Juan Metropolitan Area are examined in the following maps, and then discussed:

Figure 26: Percent of Owner Occupied Households with no Vehicle Available

Percent of Owner Occupied Households with no Vehicles Available
Analysis of Exposure to Sea Level Rise

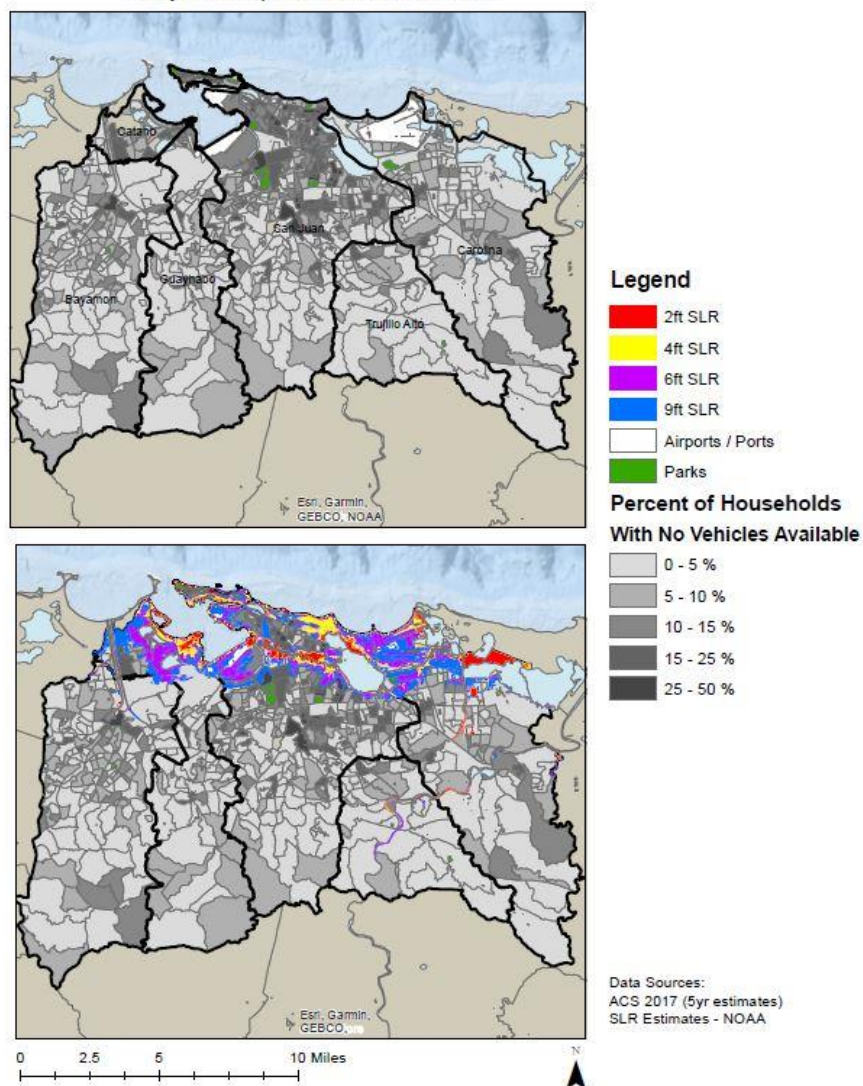


Figure 25: Percent of Renter Occupied Households with no Vehicles Available

Percent of Renter Occupied Households with no Vehicles Available
Analysis of Exposure to Sea Level Rise

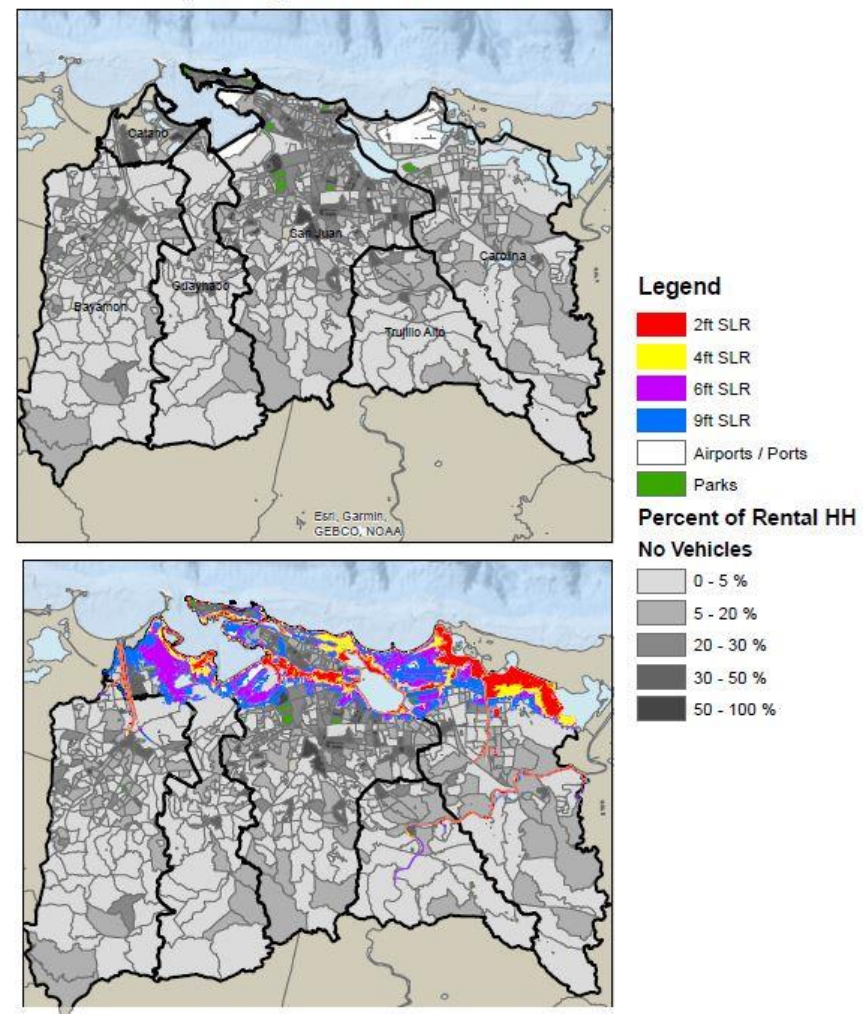
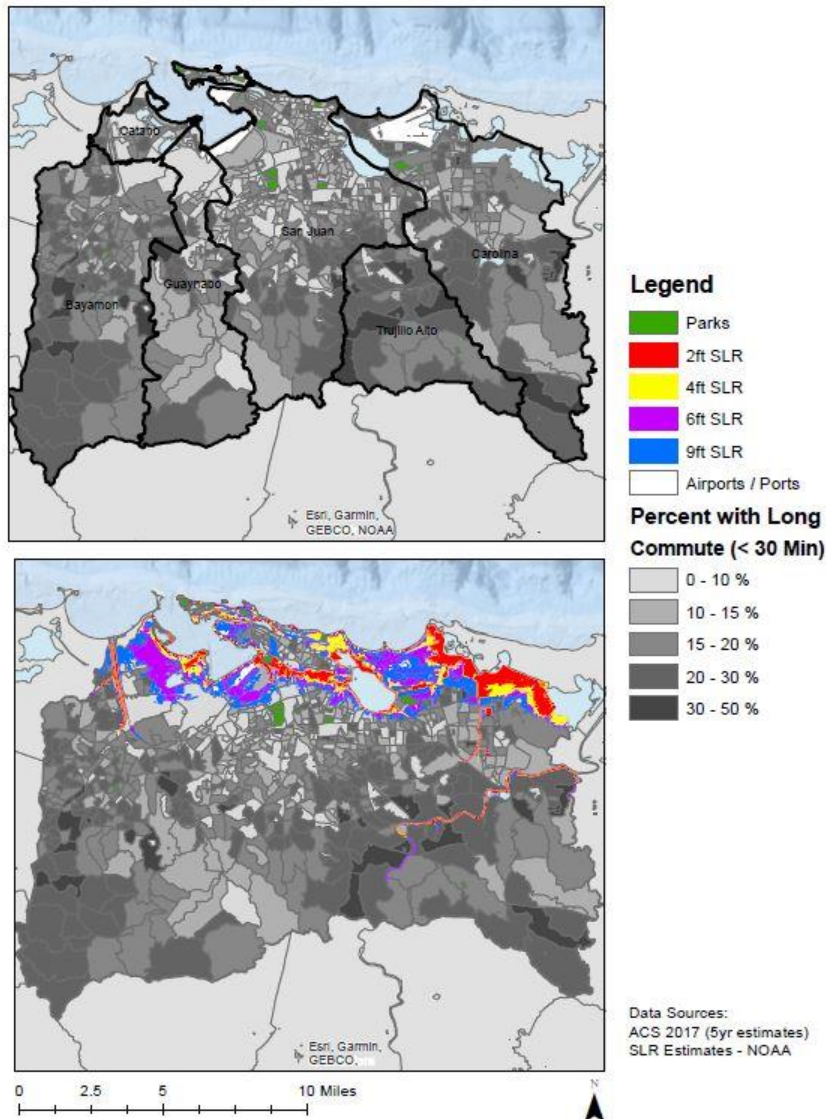


Figure 27: Percent of the Population with a Long Commute (>30 min) to work

Percent of Population with Commutes to Work over 30 minutes
Analysis of Exposure to Sea Level Rise



Data Sources:
ACS 2017 (5yr estimates)
SLR Estimates - NOAA

Transportation Disadvantaged Communities - Discussion:

Owner-occupied households with no vehicles available are concentrated mainly in the central and northern region of the Municipality of San Juan, along the San Juan peninsula, and in the Municipality of Cataño near the shoreline. There are also tracts in the suburbs where between 10 and 15 percent of the households do not have vehicles available. A similar pattern appears for renter-occupied households. A large portion of these tracts are vulnerable to SLR and storm surge scenarios. Lack of access to vehicles may limit their ability to evacuate before a storm or mobilize afterwards.

Tracts with high percentages of the population with long commutes are located principally in the outskirts of the San Juan Metropolitan Area, particularly in the extreme southwestern, southern and southeastern regions. Another area where this population is concentrated is in Carolina, near the Luiz Muñoz Marín Airport.

The distribution of these socially vulnerable and transportation disadvantaged communities, and their exposure to SLR and storm surge scenarios is important for long-range transportation and land use planning. This analysis attempts to build upon and enhance the EJSscreen by adding indicators that are specific to Puerto Rico, hazard research, and transportation disadvantaged communities. The following maps compare the original EJSscreen and the new composite index generated through this analysis.

Figure 29: Original EJSCREEN

EPA Environmental Justice Screen Composite Index (EJSCREEN)
Analysis of Exposure to Sea Level Rise

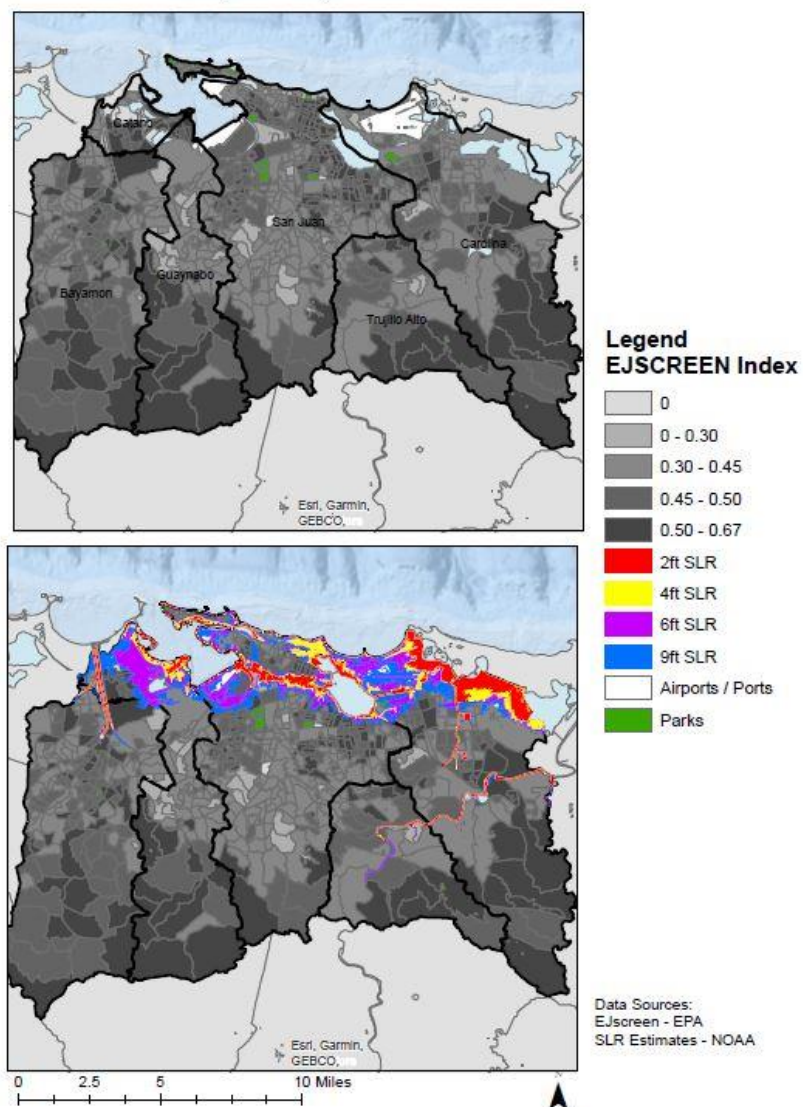
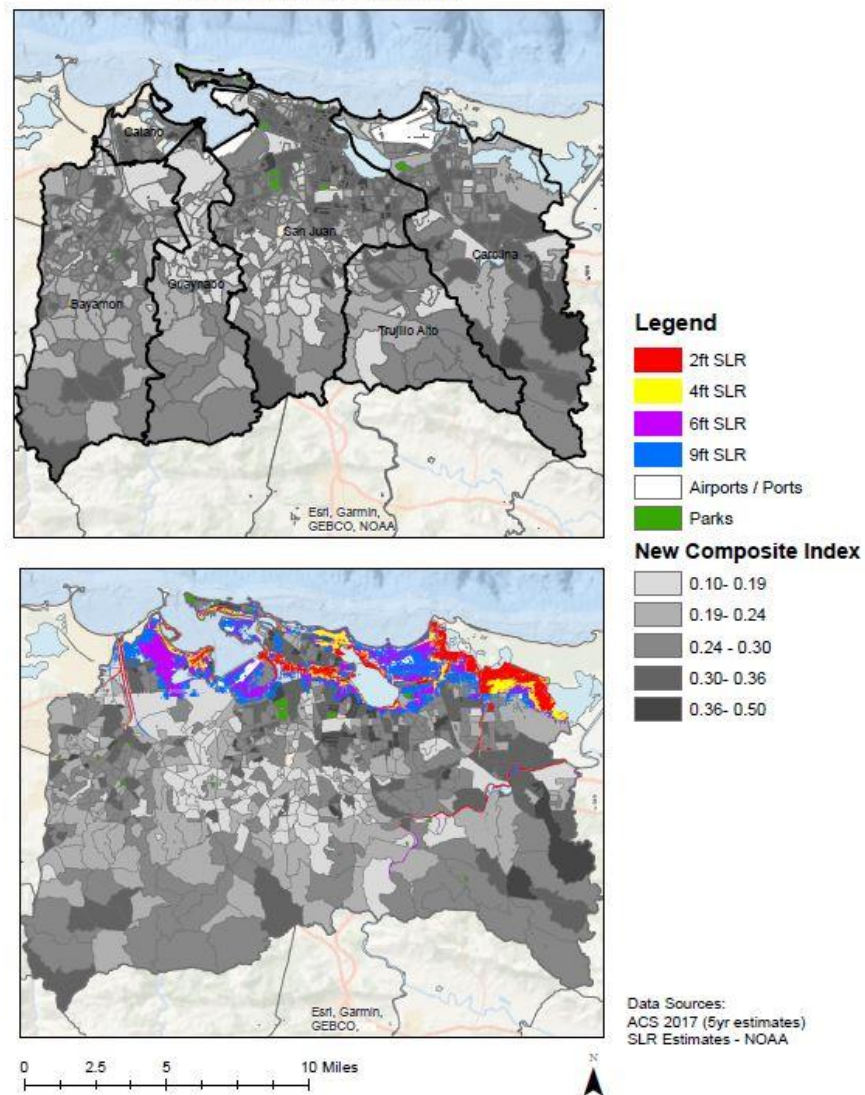


Figure 28: New Composite Index

New Composite Index (9 Indicators)
Analysis of Exposure to SLR



EJSCREEN comparison with New Composite Index – Discussion

Some important observations can be made by examining the EJSCREEN and the composite index side by side. First, the two indexes reflect quite different pictures. The EJSCREEN seems to reflect a stronger pattern of social vulnerability in the suburbs and around the periphery of the San Juan Metropolitan Area. It also highlights pockets around El Caño Martín Peña, the periphery of the San José lagoon, and parts of the San Juan peninsula. The adjusted 9-indicator index retains some of these patterns, and continues to highlight areas in El Caño Martín Peña, the periphery of the San José lagoon, Cataño, and the San Juan Peninsula. However, the map appears lighter overall, and there isn't as distinct a pattern observed in the suburban and peripheral regions of the city. Moreover, the original index has a higher overall range (0 – 0.67), while the new index has a lower range (0- 0.50).

Several factors may explain the observed differences between the two indices. First, the EJSCREEN index includes the minority and linguistically isolated variables that are deemed inappropriate in the context of Puerto Rico and have been excluded from the new index. These variables may in some way skew or exaggerate the EJSCREEN index. Second, upon closer examination, the new index may include variables that somehow cancel each other out. For example, Figures 25 and 26 show that the majority of households in the suburbs have at least one car, even if they are also low-income, as demonstrated by figure 18. These people are likely spending a disproportionate share of their income on a vehicle because as figure 9 shows, these peripheral neighborhoods are not well serviced by the public transportation infrastructure. Figure 27 confirms that many people residing in these neighborhoods have a long (>30 minute) commute to work. However, in the new composite index, some of these nuances are canceled out.

These observations point to the possible limitations of the new composite index, and they also warn against relying too heavily on indicators in making planning and policy decisions in general. As Litman argues, “The use of indicators is just one step in the overall planning process, which includes consulting stakeholders, defining problems, establishing goals and objectives, identifying and evaluating options, developing policies and plans, implementing programs, establishing performance targets, and measuring impacts” (Litman, 2007). Nonetheless, Litman acknowledges that planners also rely on indicators to understand the context, establish baselines, observe trends, and evaluate outcomes of policy decisions. He also acknowledges that they can be useful for incorporating considerations of equity (Litman, 2007). As such, indicators are somewhat of a double-edged sword and must be treated with care, and not overly relied upon.

Comparing the EJSCREEN and the new, 9-indicator index, this study recommends that it may be best for planners and policy-makers to continue to use the EJSCREEN index in their desktop analysis, in order to begin incorporating considerations of equity when planning for SLR and storm surge. Researchers may consider continuing to experiment with a more locally appropriate index for Puerto Rico, such as one that excludes the ‘minority’ and ‘linguistically isolated’ variables. It may also be useful to explore separate indexes for the transportation disadvantaged groups.

At the same time, at the Metropolitan Area level at least, it seems relatively simple and useful to look at each indicator individually. An added value of this study is that each variable is analyzed separately. The maps generated may be useful materials for understanding at a glance how different populations are distributed and their exposure to the impacts of SLR and storm surge. These maps, coupled with an analysis of the transportation infrastructure exposed to SLR and storm surge, have important

implications for planning and policy in the San Juan Metropolitan Area, as further unpacked in the following section.

5. Discussion and Recommendations

The fourth objective of this study is to discuss implications of the findings from the literature review desktop analysis for plans related to transportation in Puerto Rico, with an emphasis on the effective use of federal expenditures post Hurricane Maria. The study has revealed several important findings from the literature and desktop analysis. The literature review summarized the state of knowledge on climate change, implications for the transportation sector, methods for incorporating considerations of social vulnerability, environmental justice, and transportation disadvantaged populations in analysis, as well as background on Puerto Rico, the impact of Hurricane María on the island, and the status of current planning documents relevant to the transportation sector. The desktop analysis examined both transportation assets and characteristics of communities exposed to inundation under different SLR and storm surge scenarios. This discussion briefly summarizes findings from throughout the study and draws on them to make planning and policy recommendations.

Findings from the IPCC and National Climate Assessment reports reveal that there are large ranges in uncertainty in the climate science. Regarding SLR specifically, even under low emissions scenarios (RPC 2.6), global mean SLR is expected to be between 0.5 and 1 foot by mid-century, and up to 2 feet by 2100. High emissions scenarios (RCP 8.5) project global mean SLR (GMSLR) to be at least 1 foot by mid-century, and possibly over 3 feet by 2100. However, these scenarios do not account for unknown or sudden changes in the climate system. There might be rapid feedback loops, tipping points, or triggers that send the climate into new unknown states. For example, some models estimate that rapid melting of the ice caps in Greenland and Antarctica, for example, may result in GMSLR up to 8 feet (Fleming et al., 2018). Further, a review of the science shows that there is significant amount of local variability in projections due to climatic variation. Researchers in Puerto Rico and the Caribbean region have noticed acceleration in recent years, and have adopted more aggressive ranges of uncertainty, with high emissions scenarios (RCP 8.5) resulting in as much as 9 to 11 feet of SLR by 2100 (Díaz et al., 2018, p. 20). SLR is expected to significantly exacerbate the damaging effects of storm surge, wind, and wave action. A recently released draft report that updates the Draft - Updated Multi-Risk Mitigation Plan for the MSJ estimates that a category 5 hurricane could cause storm surge of up to 18 feet (MSJ, 2018). Hurricane María, a category 4 hurricane, brought storm surge of up to 9 feet in some parts of the island (Government of Puerto Rico, 2019).

Given these findings from the literature on SLR and storm surge, it is imperative that the transportation sector acknowledge and plan for wide ranges of uncertainty in climate impacts on the system, both at the metropolitan, island-wide level, and at the national level. This paper conducted a basic desktop analysis to examine the exposure of transportation assets in San Juan under different SLR bathtub scenarios, specifically intersecting assets and routes inundated at 2ft, 4ft, 6ft, and 9ft SLR scenarios. Findings reveal that under a 9ft SLR or storm surge scenario, almost 400 miles of roadway, a mile of train, almost 50 miles of 'público' routes, and almost 140 mile of bus routes are exposed. While these numbers represent less than half a percent of the road network, 8 percent of the train route, 6 percent of the 'público' routes, and 22 percent of the bus routes in the San Juan Metropolitan Area, these are

some of the most densely populated areas in San Juan. Many of the coastal corridors are vital to the economy of the city and are home to job centers, government buildings, and critical lifeline infrastructure. As such, interruptions to these road and transit networks could have foreboding cascading consequences for the island.

Further, a cursory analysis of the ports and airports show that these important assets are almost all completely overtopped by the 9ft scenario. This represents a significant danger to the Puerto Rican population, which relies on ports and airports for emergency functions such as evacuations and the distribution of food, water, and other first responder services. The risk these assets pose to the future of the San Juan region cannot be overstated. As Dr. Catherine Ross, an internationally recognized expert on transportation systems planning states, airports and ports today represent “the glue of the global economy” (personal communication and advising, Ross, 2019). If future SLR and storms halt operations at the ports and airports of San Juan, the island-nation will be even more isolated from the rest of the world, putting the economy and society at risk.

Given the ranges of uncertainty in future SLR and storm surge projections, and the fact that the island has already experienced storm surge of 9ft, this study recommends that transportation plans across the island adopt aggressive measures to mitigate against flood risk due to climate change. Planners and decision makers should make efforts to align plans and adopt a common understanding of risk, and levels of tolerable risk. At the time of writing this paper, the most aggressive and advanced plan is the *Draft - Updated Multi-Risk Mitigation Plan for the Municipality of San Juan*, which considers SLR scenarios up to 11 feet by 2100 and acknowledges risk of up to 18 feet of storm surge in a category 5 hurricane. These risks should be incorporated in the upcoming *Comprehensive Transportation Plan for the Municipality of San Juan* for which an RFP has been released, as well as the next *Puerto Rico Island-wide Long-Range Transportation Plan*, last published in 2013 and likely due for an update.

More pressingly, documents like the PRHTA Final Fiscal Plans must align with local projections of risk and long-standing land use and transportation planning visions. This Plan aims to obligate \$3.1 billion in capital expenditure to improve and repair transportation infrastructure on the island post Hurricane María between FY2018 and FY2023. However, the document does not mention future climate risks and projections, and there may be risk in re-investing in systems that have already proven to fail under storm conditions. These recovery documents are being developed in a resource-constrained environment and shaped by deadlines and demands from the federal government. Combined with the anti-science stance of the current President, these time and resource constraints likely put pressure to justify expenditures in the name of economics and efficiency instead of acknowledging themes of uncertainty and equity. Where possible, career employees at the federal level should seek to create an environment that encourages plan alignment. There should be special focus on adopting projections of risk and uncertainty based on observed change at the local and regional level.

Furthermore, in plans like the *PRHTA Final Fiscal Plan 2018-2023*, this report finds that a disproportionate amount of the obligations are aimed at highway infrastructure, with less than 0.5 percent of total obligations oriented towards transit. This fact raises important questions about equity in future investment in the transportation system. This study has experimented with methods to incorporate equity into transportation planning studies based on findings from the literature. Several important findings emerged from both the literature and the desktop analysis. First, there are easily accessible data sources at the federal level that allow for quick and simple integration of equity

considerations into all planning decisions. Namely, the EJSCREEN tool developed by the EPA allows planners to quickly screen communities based on six demographic indicators deemed relevant to social vulnerability and environmental justice issues (low-income, minority, linguistically isolated, less than high school education, under age 5, and over age 64). The EPA compiles these indicators at the block level throughout all communities in the United States, including territories like Puerto Rico. While this study revealed a few potential limitations of the tool, it still highly recommends using this tool for incorporating a brief desktop equity analysis into all transportation planning studies.

An added value of this current paper is that it has produced maps displaying the distribution of each one of these indicators in the San Juan Metropolitan Area, overlaid with SLR projections. Furthermore, this paper went beyond examining the indicators selected by the EPA, and examined additional indicators based on the local context, hazards literature, and literature on transportation disadvantaged communities. The study experimented with rolling all of these indicators into a composite index but found limitations in that some variables may accidentally cancel each other out. As such, planners may glean more insight from the individual analysis of each indicator and exposure to SLR, as well as relationship to transportation assets. The paper warns against over-reliance on indicators, which cannot serve as a substitute for other methods, like meaningful public outreach and involvement.

Overall, the desktop equity analysis revealed that there are clusters of socially vulnerable populations living in areas subject to SLR and storm surge, specifically around the Caño Martín Peña and the border of the San José lagoon, along the north bank of Cataño, south of the airport, and in parts of the San Juan peninsula. Future transportation planning should coordinate with land use planning to consider managed retreat and relocation for communities living in these risky areas, and the provision of proper public transportation services to meet their needs. While beyond the scope of this study, an interesting case study in community-based relocation planning is being carried out in the Caño Martín Peña communities, led by a partnership between community leaders, a land trust, and an independent government organization called ENLACE (Rodriguez, 2017).

The equity analysis also reveals that there are clusters of socially vulnerable populations located in the suburbs and around the periphery of the San Juan Metropolitan Area. While these populations are not at risk to SLR and storm surge, they also have significantly less access to public transportation services. These populations may be forced to spend a large proportion of their income on an automobile out of necessity, and they may suffer longer commutes to work. Future transportation planning should consider expanding public transportation service to these areas, in coordination with land use planning.

6. Limitations and opportunity for future research

While this study has relevant and timely implications for transportation planning in Puerto Rico post Hurricane María, it also has several limitations. First, the study provides only a cursory desktop analysis of exposure under different SLR scenarios based on a bathtub model. The study could be significantly enhanced by considering more sophisticated projections of storm surge by considering wind and wave action that might push water further inland. Based on findings from the Draft - Updated Multi-Risk Mitigation Plan, scenarios of up to 18 feet in storm surge are possible under a category 5 hurricane. As such, future analysis should consider assets that might be exposed in these conditions. In addition, another limitation of the bathtub model is that it does not take into account possible exacerbations due to extreme precipitation and flash floods.

Second, the study does not take into account structures like bridges, culverts, and tunnels. Obtaining data on these types of assets and their elevation was beyond the study scope but should be incorporated into more sophisticated analysis. Similarly, the elevation of the Tren Urbano train tracks and platforms was not taken into account. It is likely that this has exaggerated the length of the section that intersects with the SLR projections. Nevertheless, there are important operations and infrastructure at the ground level that might be affected.

Third, the study could be significantly enhanced by defining metrics of criticality for segments of the transportation system. For roads, criticality metrics might include characteristics like annual average daily traffic (AADT), vehicle miles traveled (VMT), level of service (LOS) or their role in connecting vulnerable populations with lifeline infrastructure like hospitals, for example. The criticality of public transportation assets could similarly be measured as a function of ridership and connectivity.

Fourth, the study could expand analysis of additional indicators of social vulnerability and transportation disadvantaged communities. One important indicator that was left out of this study was the disabled population. This is an important population to consider, as they are particularly vulnerable to hazards and typically have a higher dependency on transit systems than the general population. Data at the block level is available upon request through IPUMS, but uses a different unique ID than ACS data, making map integration difficult within the scope of this study.

Finally, this study relies solely on a simple desktop analysis and does not include input from local transportation planners or professionals nor the general public. Planning analysis is incomplete without these perspectives, but such research was beyond the current scope. Future research could build off this analysis by conducting interviews with key stakeholders, survey analysis, and field research, for example.

7. Conclusion

When it comes to transportation planning, Puerto Rico is at a crossroads. Hurricane María has simultaneously crippled the transportation infrastructure and opened up funding opportunities that could transform the system for the better. The island needs to carry out a coordinated and judicious planning effort to ensure that once-in-a-lifetime allocations are well spent to better serve the public now and in the future. First, this involves incorporating new ranges of uncertainty emerging from the science about the potential impacts of climate stressors, including SLR and storm surge. Planners and decision-makers at all levels of government should work towards a common understanding of the ranges of uncertainty and tolerable risk. Documents like the IPCC reports, National Climate Assessment Reports, and the Draft - Updated Multi-Risk Mitigation Plan for the Municipality of San Juan provide important guidance about risk and uncertainty that all levels of government should take into consideration.

Second, the proper allocation of public funds for transportation investments requires considering equity, environmental justice, and the needs of transportation disadvantaged communities. A preponderance of easily accessible data at the block group level, and tools like the EJSCREEN make it a simple task to screen for these types of populations. The desktop analysis in this paper analysis several of these indicators individually, and the maps may be useful to decision makers considering how to invest federal dollars. The report recommends that planners and decision makers seek to rebuild the system to reduce car-dependency and expand public transportation opportunities. Instead of less than 0.5 percent going to transit as proposed in the PRHTA Final Fiscal Plan 2018-2023, this report proposes that a much larger proportion be dedicated to enhancing public transportation.

Transportation has the potential to be a platform of recovery and growth on the island, but this can only occur if planning continues to adapt to a constantly changing reality. By incorporating themes of uncertainty and equity across planning documents and initiatives, Puerto Rico could become a model for sustainable and inclusive transportation planning in a complex, resource constrained, post-disaster environment.

8. References

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